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Using Value-Focused Thinking to Evaluate the Use of Innovative Stormwater Management Technologies on Air Force Installations

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USING VALUE-FOCUSED THINKING TO EVALUATE THE USE OF INNOVATIVE STORMWATER MANAGEMENT TECHNOLOGIES ON AIR FORCE INSTALLATIONS

THESIS

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Abstract

Stormwater runoff occurs naturally after every storm event; however, traditional development practices have created many impervious surfaces, such as buildings, parking lots, and streets that increase runoff volume and flow rate. Conventional stormwater management practices focus on collecting runoff into centralized channels and conveying it as quickly as possible to local bodies of water. This type of conveyance system decreases the opportunity for stormwater to naturally infiltrate back into the ground. It also prevents contaminants from being naturally filtered out of stormwater flows. As a result, centralized conveyance systems can cause flooding, erosion, and terrestrial and aquatic habitat degradation. Innovative stormwater management strategies treat stormwater on-site by encouraging infiltration, decreasing flow rates, and reducing pollutant loads.

Value-Focused Thinking (VFT) was used in this research to develop a decision analysis model to assist Air Force decision makers in evaluating and selecting innovative stormwater management strategies. VFT is a multi-objective decision analysis model that compares alternatives based on the values of the decision maker. Nine stormwater technologies were evaluated across thirteen evaluation measures. Through deterministic analysis and sensitivity analysis, a grassed swale was found to be the top alternative, followed very closely by the infiltration basin and wet detention options. VFT proved to be a useful methodology in producing an objective solution to this complex, multi-objective decision problem.

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2Lt Jeffrey T. Falcone

Table of Contents

List of Figures

List of Tables

USING VALUE-FOCUSED THINKING TO EVALUATE THE USE OF INNOVATIVE STORMWATER MANAGEMENT TECHNOLOGIES ON AIR FORCE INSTALLATIONS

1. Introduction

1.1. Overview

Stormwater runoff is the result of a disruption in the natural infiltration process both during and after rainfall or snowmelt events. Water naturally flows over the ground where it has the opportunity to infiltrate the surface and recharge ground water supplies. Runoff is water that does not enter the ground through infiltration. Stormwater runoff flows over the earth's surface until it enters a local stream, river, lake, or other body of water. Although runoff is a natural part of the hydrological process, developed areas significantly increase the amount of impervious surfaces which prevent infiltration of rain and snowmelt. Streets, roofs, parking lots, sidewalks, athletic courts, and even well manicured lawns are just a few examples of the impervious surfaces that replace naturally occurring grasslands and forests in urban areas. These areas usually have stormwater systems that attempt to collect and move the runoff in order to promote rapid draining. These conventional stormwater conveyance systems decrease the opportunity for groundwater recharge and also increase runoff volume (EPA, 2000). Stormwater runoff is a concern for two reasons. One issue deals with volume while the other is related to pollutants. When runoff is collected and conveyed in a central system, the large volume and rapid flow can cause flooding, erosion, and both terrestrial and aquatic habitat degradation. While runoff flows over impervious surfaces, it picks up contaminants.

"These pollutants are carried with the runoff into surface waters where they adversely impact water quality" (MD DNR, 1995).

Traditional development methods in common use today result in the creation of large expanses of impervious areas. "Low-impact development (LID) integrates environmental concerns with land development, focusing on water and pollutant balance" (Davis, 2005). LID differs from traditional development methods in that it attempts to prevent modification of the natural hydrologic cycle. Part of LID is implementing best management practices (BMPs). Whereas traditional stormwater management methods use "curbs, gutters, and storm drains to move water off-site as efficiently as possible," LID uses BMPs to take "advantage of a site's natural features – including vegetation" to encourage infiltration of runoff, reduce stormwater volume, and improve water quality (MD DNR, 1995). Structural BMPs used for post-construction runoff controls are divided into four main categories: detention systems, infiltration systems, vegetative filtration systems, and specialty devices (Debo and Reese, 2003). Each of these categories reduces stormwater quantity and/or enhances water quality. Vegetative BMPs also improve natural site hydrology and increase aesthetic appeal (EPA, 1999a). Structural BMPs can reduce the need to build a costly traditional stormwater control infrastructure.

1.2. Background

The Clean Water Act of 1972 (CWA) and its amendments in 1987 are the primary sources of legislation that focus on water pollution issues today. Stormwater management and regulation fall under the EPA's efforts to enforce the various goals and policies of the Clean Water Act. Stormwater is officially defined as "storm water runoff, snow melt runoff, and surface runoff and drainage" (CFR, 2005). The Clean Water Act prohibits the discharge of pollutants into any U.S. body of water unless it is an approved discharge. Approved discharges must be permitted under the National Pollutant Discharge Elimination System (NPDES). "The NPDES permit program implements the Clean Water Act's prohibition on unauthorized discharges by requiring a permit for every discharge of pollutants from a point source to waters of the United States" (Sullivan, 2003). Stormwater that is collected or channeled falls under the definition of a point source. The CWA requires that industrial areas, municipalities of all sizes, and construction zones of all sizes must file for a NPDES permit. These areas must also apply best management practices (BMPs) in order to comply with water quality standards (Sullivan, 2003).

The EPA defines a BMP as "a technique, measure, or structural control that is used for a given set of conditions to manage the quantity and improve the quality of storm water runoff in the most cost-effective manner" (EPA, 2006). BMPs are divided into two categories: non-structural and structural. Non-structural BMPs are operating rules and procedures that minimize the amount of stormwater pollution that is produced. A few examples of non-structural BMPs are preventative maintenance, community education programs, and pollution prevention procedures. Structural BMPs are "engineered controls that remove pollutants from storm water and usually include specially constructed devices/systems" (PRO-ACT, 2006). Examples of several structural BMPs in use today include green roofs, porous pavements, grassed swales, bioretention basins, and oil-water separators.

Innovative stormwater management strategies, including the use of structural BMPs, have been very successful in decreasing runoff volume and increasing water quality in many locations throughout the United States. Numerous private entities, as well as municipalities, are implementing alternative stormwater management plans. However, because conventional management viewpoints have focused on conveying stormwater off of streets and parking lots as quickly as possible, widespread use of alternative structural BMPs is not possible without adopting a new stormwater management philosophy. This necessary philosophy sees water as a valuable resource that must be protected and conserved. It also looks at the natural hydrologic cycle for an example of management through natural volume reduction and filtration (PWUD, 2006). Several concerns that oppose implementation of LID and alternative BMPs are the perceived lack of flood protection provided, possibility of complete system failure, a lack of expertise in installation and maintenance, market place acceptance, and cost-effectiveness (Lloyd, Wong, and Porter, 2002).

One sector of the population that has seen an increase in the use of LID is the federal government. The Pentagon was remodeled with the use of a variety of LID and sustainable design features including a green roof and permeable pavements (Gawlik, 2005). The U.S. Air Force is the nation's leading consumer of green power. In 2001, the Air Force's Sustainable Development Policy letter was published. It stated that Air Force policy is to use sustainable development "consistent with budget and mission requirements" (Robbins, 2001). Stormwater management is addressed in this policy through the inclusion of the terms "conserve water" and "prevent environmental degradation." The letter also states that it is the Air Force's policy to use the United

States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED™) Green Building Rating System as a self-assessment tool to rate Air Force facilities. Projects earn LEED™ credits for including the following: water efficient landscaping which use collected stormwater for irrigation; sediment and erosion controls such as swales or retention basins; and BMPs that limit stormwater runoff volume and flow rate, promote infiltration, and naturally treat site stormwater (USGBC, 2002). Although the Air Force uses LEED™ as a self-assessment tool, it is not committed to actually submitting projects for approval. This means that a real incentive to make use of alternative stormwater BMPs on Air Force installations may be lacking.

1.3. Problem Identification

For decision makers on Air Force bases that do consider implementing alternative structural stormwater BMPs, there are currently no decision making guidelines which they can follow to evaluate and select innovative technologies. The purpose of this study is to identify and evaluate several structural BMPs for use on Air Force installations. The research will highlight environmental and economic differences between traditional and alternative stormwater management, and will also develop a decision making model to assist Air Force decision makers in evaluating and choosing structural BMPs for inclusion on their base. For those who have no knowledge of innovative stormwater management strategies, this study will provide a background for why they should be used and a framework for choosing them. The decision model will be applied to choosing stormwater management strategies for a new academic building currently under construction at the Air Force Institute of Technology on Wright-Patterson Air Force Base.

1.4. Research Questions

Five research questions are proposed below in order to guide this research and to develop a meaningful decision analysis model.

1. What environmental and economic concerns are associated with stormwater runoff in developed areas?
2. What innovative stormwater management technologies have been used successfully in the past?
3. What features, advantages, and disadvantages exist for specific innovative stormwater management technologies?
4. What are Air Force decision makers' values when selecting stormwater management strategies?
5. Is Value-Focused Thinking an appropriate decision making methodology for selecting stormwater management technologies for use on Air Force installations?

1.5. Research Approach

The research questions above will be addressed in this study by performing an extensive literature review and a decision analysis. Questions 1, 2, and 3 will be answered in the literature review of all relevant information pertaining to stormwater, applicable policies and regulations, case studies, and reviews of the BMPs of interest.

Questions 4 and 5 will be addressed partly in the literature review, but more extensively in the decision analysis process. Decision analysis is the discipline for systematically making complex decisions considering alternatives, uncertainties, values, and preferences (Knighton, 2006). In this research, decision analysis will be performed to give insight to Air Force water managers in order to choose structural BMPs for stormwater management associated with parking areas. Quantifying advantages and disadvantages of various BMPs enable them to be compared on a similar scale, which permits a decision maker to perform a meaningful evaluation of alternatives. In this research, BMPs will be evaluated through the use of Value-Focused Thinking (VFT). VFT is a "structured method for incorporating the information, opinions, and preferences of the various relevant people into the decision making process" (Kirkwood, 1997: 1). VFT is a strategic, quantitative approach to decision making that relies on specified objectives, evaluation considerations, evaluation measures, and value hierarchies (Kirkwood, 1997: 12). Values are defined as the issues that are important to the decision maker. The VFT process is a sequence of five activities: recognize a decision problem, specify values, create alternatives, evaluate alternatives, and select an alternative (Keeney, 1992: 49).

1.6. Scope

As of 2002, 70 different BMPs were being used in Australia, New Zealand, and the U.S. (Taylor and Wong, 2002). Clearly, Air Force decision makers have a wide variety of options to choose from when implementing BMPs in compliance with NPDES permitting. Because non-structural BMPs are already widely used on Air Force bases, this research focuses on evaluating on-site structural BMPs as part of an innovative stormwater management plan. Since there is a multitude of structural BMPs to choose from, the study focuses on technologies that are of greatest interest to the specified decision maker. After completing the Alternative Development step of the Value-Focused Thinking process, as explained in Chapter 3, the following stormwater management practices were chosen for evaluation: wet detention, oil-water separator, infiltration basin, infiltration trench, rain garden, open space design, constructed sand filter, grassed swale, and vegetated filter strip. In prior research, Bulson found that traditional asphalt and concrete are generally preferred to porous pavement alternatives on Air Force installations (results subject to geographic location) (Bulson, 2006); therefore, this study does not evaluate the use of porous pavements as a structural BMP.

Since VFT models are specific to the problem rather than to the alternatives they evaluate, other BMPs can be evaluated with the model in the future if a decision maker wants to analyze other options. However, if different decision makers use this model, it is necessary to re-evaluate, and adjusted if necessary, the weight of each value in the model. Weighting is a subjective process and must be performed specifically for each decision maker in order for the model to accurately reflect preferences and decision context.

1.7. Significance

This research contributes to the body of knowledge that Air Force decision makers have available when making stormwater management decisions. It not only provides a framework for making such decisions, but creates a general awareness of innovative structural BMPs that are available for use when constructing, repairing, or replacing stormwater infrastructure. This study presents various cases where innovative technologies have successfully been used in the past. It also presents construction and maintenance cost data for each BMP discussed. The Air Force's commitment to pursue sustainable development principles and its observance of Air Force Instruction 32-7041 (Water Quality Compliance) justifies the completion of this study.

1.8. Summary

The past two decades have seen a tremendous increase in impervious surfaces as part of urban and industrial development (EPA, 2006). The EPA estimates that a typical city block generates over five times more stormwater than a woodland area of the same size. If left unchecked, such rapid development and its associated impervious areas accelerate erosion, cause flooding, destroy plant and animal habitat, and degrade water quality. Every member of society, from the local citizen to the largest industrial entity, is responsible for helping to solve this problem.

Stormwater management is very important to daily Air Force operations since large areas of installations are covered with impermeable surfaces. Although current practice is to collect runoff in a traditional curb, gutter, drain, and pipe system and then transport the water to a local body of water, several structural BMPs exist which can reduce base stormwater quantity and improve the area's water quality. The decision analysis model developed in this study can aid Air Force decision makers in choosing appropriate stormwater BMPs to implement at their respective locations.

2. Literature Review

2.1. Overview

This literature review is a consolidation of relevant information published on stormwater, stormwater management, and value-focused thinking. It provides answers for research questions one, two, and three and also provides a background for research questions four and five. The chapter is divided into four sections including stormwater background, traditional management practices, alternative management practices, and value-focused thinking.

2.2. Stormwater Background

Stormwater runoff is part of the natural hydrologic cycle. After rainfall or snowmelt events, water travels over the earth's surface where it infiltrates into the soil, evaporates, is absorbed by vegetation, or is collected in a body of water. Figure 1 is a schematic of the natural hydrologic cycle. In an undeveloped area, most stormwater soaks into the ground, is naturally filtered underground, and then feeds streams, lakes, and underground storage. Urban development greatly impacts this natural cycle. Figure 2 shows the difference in the water cycles of undeveloped areas and various urban areas. The construction of roads, parking lots, roofs, compacted soils, and all other impervious surfaces results in an increase in runoff volume and flow rate (UFC, 2004). When meadows and forests are replaced by impervious surfaces, water can no longer penetrate the earth's surface. Instead, rain or snowmelt is collected in drains, ditches, or streams without undergoing the natural filtration process. Such runoff carries pollutants into local bodies of water, increases erosion, and causes flooding. Runoff can have serious impacts on both human and environmental health. These issues are the basis for all stormwater research and management efforts.

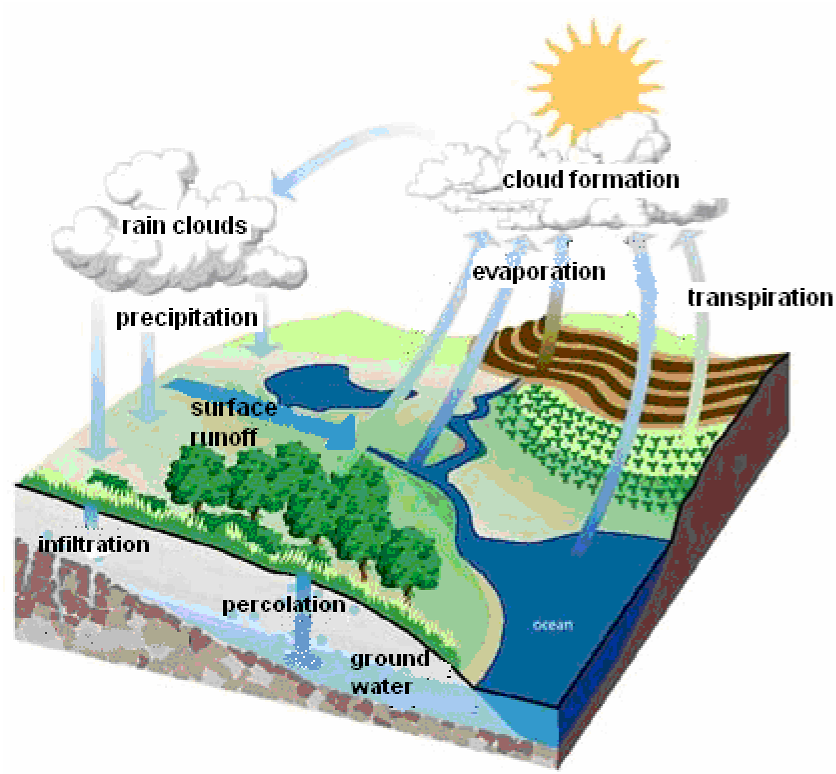

Figure 1: Natural Hydrologic Cycle (EPA, 2006b). Surface runoff is a normal part of the natural hydrologic cycle.

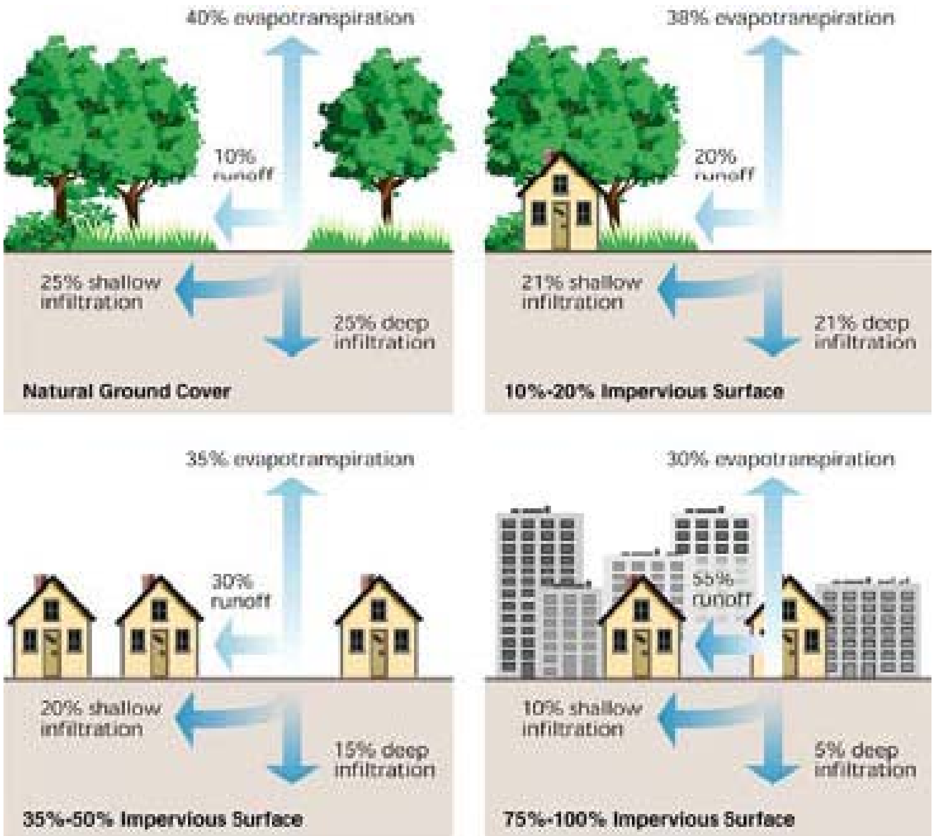

Figure 2: Comparison of Water Cycle across Varying Levels of Development (PWUD, 2006).

2.2.1. Problems

Increased volume and flow rate of stormwater runoff currently presents many problems for communities throughout the world. Growing populations and the resulting development are creating fewer natural areas in which the water cycle is undisturbed. The movement of Americans in the later half of the twentieth century from cities to suburbs has resulted in a drastic increase in the amount of impervious surfaces in the United States. In fact, it is estimated that impervious area is still increasing at a rate of 250 square miles per year in the U.S. alone (Ferguson, 2005). As it is estimated that a parking lot sheds sixteen times the amount of water that a meadow does (NC DENR, 2006), it is imperative to have stormwater management infrastructures that limit the amount of environmental degradation that results from stormwater.

The increase in stormwater runoff in developed areas has a profound effect on water quality because it increases the amount of suspended solids, petroleum products, residues from industrial activities, litter, nutrients, and pet waste that are carried into receiving waters (MDNR, 1995). Many of these substances, such as oil and fertilizers, are harmful in any quantity, while others, such as grass clippings and pet waste, are harmful only in sufficient quantities. When runoff flows to rivers through curbs, gutters, and storm drains, it not only picks up pollutants, but also accelerates erosion which causes flooding, destruction of plant and animal life, and loss of habitat.

The mix of sediment and pollutants in stormwater undoubtedly causes problems downstream for both humans and animals. Sediment from erosion covers up wildlife habitats while chemicals, such as fertilizer, can upset the natural chemical balance of the water. Unfiltered stormwater also creates problems for drinking water supplies, as well as for aquatic recreation areas. Pollutants carried to receiving waters enter the food chain where they can build up in the tissue of fish, possibly being consumed by humans. Without proper management, water treatment costs rise, putting added financial burden on society. When water is polluted, everyone is affected (NC DENR, 2006).

2.2.2. Regulation and Policy

The Clean Water Act consists of several programs designed to restore and protect water quality in the U.S. by eliminating the discharge of pollutants into surface waters (Sullivan, 2003: 291). In conjunction with numerous federal, state, and local agencies, the EPA administers programs established by the Clean Water Act. The major components of the CWA that deal with stormwater are its prohibition on discharges, except as in compliance with the Act, and a permit program to authorize and regulate discharges in compliance with the Act (Sullivan, 2003: 293). The permit program is called the National Pollutant Discharge Elimination System (NPDES). A NPDES permit is required for any discharge of a pollutant from a point source to U.S. waters. This includes collected and channeled stormwater runoff. Because of the millions of point source discharges of stormwater, the EPA has had a difficult time regulating all discharges. The 1987 amendments to the CWA provided the EPA guidelines for how to get the stormwater permit program under control. Phase I of the NPDES program required that all industrial facilities, construction areas greater than five acres, and municipal separate stormwater sewer systems (MS4s) serving populations of greater than 100,000, obtain discharge permits (Sullivan, 2003: 320). An MS4 is defined as “a conveyance or system of gutters, ditches, man-made channels, or storm drains that is owned by a state, county, municipality, or other public entity; is designed or used for conveying storm water; and is not a combined sewer or part of a publicly owned treatment works” (Sullivan, 2003: 230). In 1999, the EPA issued Phase II of the NPDES program which required municipalities with populations under 100,000, and construction sites between one and five acres, to obtain discharge permits. The rule also mandated that these areas implement best management practices to meet water quality standards. Another change from the Phase I rule was the addition of federal and state operated MS4s (EPA, 2005a). This can include military bases that meet the definition of small MS4s.

The EPA policy is that pollution prevention is the best way to control water quality; therefore, it requires all permitees to submit a stormwater pollution prevention plan (SWPPP) for approval. A SWPPP identifies sources of pollution affecting water quality and also describes and ensures implementation of best management practices to minimize and control pollutants in discharges (Sullivan, 2003: 322). The BMPs listed in the SWPPP can be general or specific to the industry or site. Once the SWPPP is approved by the appropriate state or federal agency, the measures set forth in it are the only regulations that an organization must comply with regarding stormwater discharges.

Water quality compliance is enforced in the Air Force through Air Force Instruction 32-7041. This publication explains how to assess, attain, and sustain compliance with the CWA (DoAF, 1994). The AFI specifically states that "Installations must comply with all NPDES permit requirements. Failure to comply may result in legal enforcement action." Other documents that support pollution prevention on Air Force installations are Executive Order 12088 and Air Force Policy Directive 32-70. Because Air Force installations may contain a variety of industrial facilities, they must apply for a NPDES permit, which requires a base to develop a SWPPP. The SWPPP must list BMPs for each identified source of potential pollution (PRO-ACT, 2006). The use of innovative BMPs on Air Force installations is justified by the Air Force Sustainable Development Policy letter.

2.3. Traditional Stormwater Management

The goal of traditional stormwater management is to convey water away from its source as efficiently as possible in order to prevent property damage and to eliminate safety hazards. This is accomplished through the use of curbs, gutters, storm drains, pipes, small ditches, culverts, channels, and detention ponds. Traditional infrastructures are usually divided up into minor systems and major systems (Grigg, 2003). Minor systems make use of gutters, small pipes, small ponds, and channels. Major systems use streets, large ponds, large pipes, and an extensive network of channels. The flow from both systems are either directed to a treatment facility or sent straight to a receiving body of water. Rather than dealing with stormwater where it originates, traditional approaches capture and channel stormwater off-site. This collection results in an unnatural volume and flow rate of runoff. As it flows over impervious surfaces, collected runoff picks up pollutants. These pollutants are deposited in the local receiving body of water. The unnatural volume and flow rate also cause erosion along the flow path. Erosion results in habitat degradation, deterioration of recreational facilities, and impaired water quality.

Figure 3: Stormwater Erosion (EPA, 2006a). Erosion of stream banks often occurs over time when there are no appropriate management practices in place to prevent such degradation. Erosion results in major maintenance issues and also detracts from the aesthetics of local waterways.

In some locations, stormwater goes through a treatment process before it is combined with a river, lake, or ocean. However, collected runoff is usually conveyed to a local body of water where it enters untreated. Stormwater treatment may not be a concern in communities with effective pollution prevention plans; however, the rapid flow rate of channeled stormwater still presents numerous problems.

Figure 4: Traditional Stormwater Outlet (Duluth, 2006). Most major stormwater outlets empty into a local body of water without any treatment.

2.3.1. Advantages and Disadvantages

Several benefits of traditional stormwater management include the following: reduced flood damage and risk of life, land value enhancement, reduced traffic delays, reduced business and cleanup losses, reduced relief costs, increased recreational opportunities, greater security, and reduced health hazards (Grigg, 2003). Other benefits include expertise in installation and maintenance, and a high level of public acceptance.

Disadvantages of a traditional stormwater management approach include the following: lack of infiltration, increased pollutant load in receiving waters, erosion, high cost of infrastructure construction and maintenance, and the need to implement end-of-pipe BMPs.

2.3.2. Conventional Structural Best Management Practices

In addition to the typical infrastructure (i.e. curbs, gutters, storm drains, pipes) used in a conventional stormwater management approach, several other management devices can be employed. Traditional structural BMPs include stormwater detention basins that collect runoff, and oil-water or oil-grit separators that filter out oil, sand, and other sediment. These BMPs are useful to treat runoff originating from parking lots and roads, but do little to reduce the overall volume of stormwater created during a storm.

2.3.2.1 Oil-Water and Oil-Grit Separators

Oil/grit-water separators are typically three-stage underground retention systems. They are "hydrodynamic separation devices designed to remove grit and heavy sediments, oil and grease, debris, and floatable matter from stormwater runoff through gravitational settling and trapping" (Debo and Reese, 2003: 908). This type of treatment unit has been used extensively for industrial applications rather than for stormwater uses. Two major issues make it less appropriate for urban stormwater use: it only removes grit and oil, not other target pollutants, and it is incapable of effectively handling the variable water flows created by runoff. These treatment units have high capital and maintenance costs. Cleanout costs for a single unit can amount to $2000 per year (Debo and Reese, 2003: 910), but maintenance must be performed in order for the unit to function properly. Another concern with the use of an oil-water or oil-grit separator is that the collected pollutant may be classified as a hazardous substance, requiring special disposal. Gravity separators are effective for pretreatment for other structural treatment units, space-limited urban sites, and treatment of hot-spot runoff (Debo and Reese, 2003: 915).

Figure 5: Installing an Oil-Water Separator (SD1, 2006).

2.3.2.2 Wet Detention Basins

A stormwater detention basin is an end-of-pipe approach to management. Rather than treat water at its source, runoff is conveyed to a constructed or natural basin. Sedimentation is the primary pollutant removal mechanism. Depending on the design of the basin, it may also be capable of removing metals, nutrients, and organics (PWUD, 2006). Natural ponds or lakes and carefully constructed wet detention areas are more beneficial than basins lacking natural vegetation at removing pollutants. Although wet detention improves runoff control, it also limits further development and requires regular maintenance to remove sediments in the base of the pool. The cost of a detention basin varies, depending on the amount of construction required to prepare it to receive stormwater.

2.4. Innovative Stormwater Management

Innovative stormwater BMPs mimic the natural hydrologic cycle by encouraging infiltration, natural filtering, and groundwater recharge. The use of innovative BMPs is part of a larger land use ethic called low-impact development (LID). Whereas traditional development practices put the environment at risk by creating large tracts of impervious surfaces, LID integrates environmental concerns with land development by focusing on water and pollutant balances (Davis, 2005). LID principles are based on controlling stormwater at its source. A system of LID controls can reduce or eliminate the need for centralized BMP facilities for runoff control (EPA, 2000). Other benefits of LID practices are that they can be integrated into the infrastructure, are more cost effective, and are aesthetically pleasing (EPA, 2000).

LID practices have both environmental and economic benefits including less disturbance of the developed area, conservation of natural features, and lower costs than traditional stormwater control techniques. Innovative BMPs can save on both construction cost and life cycle maintenance costs by eliminating much of the underground collection systems associated with traditional development. However, successful implementation of LID practices depends on available space, soil permeability, land slope, and water table depth. Zoning regulations, building ordinances, and public perception may also hinder the use of LID techniques (EPA, 2000).

In addition to overall land use strategies, LID favors the use of small landscaping features and devices to simulate the natural treatment of stormwater (UFC, 2004). Individual BMPs can be used for several runoff management functions: increasing rates of infiltration, decreasing runoff flow rates, adding retention, adding detention, and improving water quality by filtering pollutants (UFC, 2004). Table 1 shows several structural BMPs and their associated functions.

Table 1: Primary Function of Several Low Impact Development Features (UFC, 2004).

Feature	Effect or Function				
	Slower Runoff	Infiltration	Retention	Detention	Water Quality Control
Soil Amendments		X			
Bioretention		X	X	X	X
Dry Wells		X	X		X
Filter Strips	X				X
Vegetated Buffers	X				X
Grassed Swales	X				X
Infiltration Trenches		X			X
Inlet Devices					X
Rain Barrels			X		
Cisterns			X		
Tree Box Filters					X
Vegetated Roofs	X			X	X
Permeable Pavers		X			X

2.4.1. Past Uses

Innovative structural stormwater BMPs are currently being utilized by many municipalities and private organizations throughout the world. Structural BMPs are being employed in all climate zones and geographic regions. They are cost-effective when compared to conventional stormwater management options and prove to have many water quality benefits as well. They are suitable management tools at multiple planning and management levels. Figure 6 shows the appropriate application level for several BMPs. Following the figure are a few examples of structural BMP use that are relevant to this research.

BMP	Level					
	Parcel		Block	Neighborhood	District	Transportation Corridor
	Residential	Commercial/ Governmental				
Bioretention Area	X	X	X	X	X	X
Wet Detention (Ponds and Lakes)		X	X	X	X	X
Dry Detention Basin		X	X	X	X	X
Filter Strip	X	X	X	X	X	X
Grassed Swale	X	X	X	X	X	X
Green Roof	X	X				
Infiltration Basin		X	X	X	X	X
Infiltration Planter	X	X				
Infiltration Trench	X	X	X			X
Natural/Native Vegetation	X	X	X	X	X	X
Pervious Pavement	X	X	X	X		X
Rain Barrels & Cisterns	X	X				
Rain Garden	X	X	X	X		
Soil Management	X	X	X	X		X
Stormwater Treatment Train	X	X	X	X	X	X
Subsurface Storage		X			X	X
Urban Forest	X	X	X	X	X	X
Vegetated Bioswale	X	X	X	X	X	X
Wetland		X	X	X	X	X

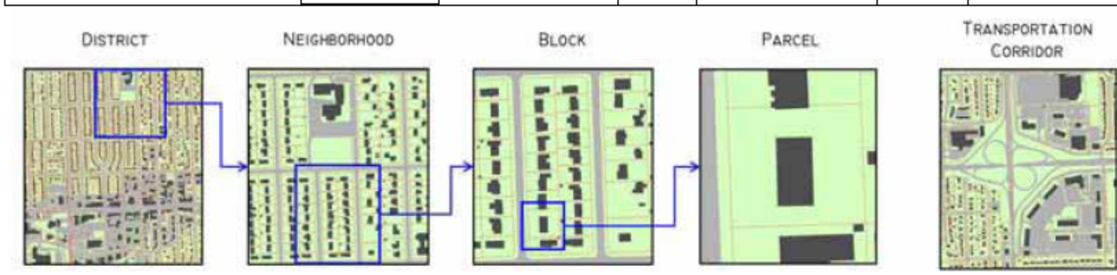

Figure 6: Suitability of BMP Applications at Multiple Planning and Management Scales (PWUD, 2006).

The Lynbrook Estates, Australia, has incorporated biofiltration systems and wetlands into the design of roads and parklands. These systems treat runoff from a 270 allotment residential precinct. The developers of the neighborhood used grassed and vegetated swales to promote infiltration as the primary treatment method. Secondary treatment is provided by a network of wetlands which discharge into a local lake. In using an innovative stormwater management design over a conventional design, the Lynbrook Estates project reported a 5% increase in cost to the drainage component of the development (Lloyd, Wong, and Porter, 2002). Since the drainage component was only 10% of the total development cost, implementing the innovative BMPs only increased the total budget by 0.5%. The developers contend that future projects will experience cost savings as contractors become more familiar with construction techniques.

The Chicago Center for Green Technology (CCGT) is on a 17-acre former Brownfield. When the city acquired the property, the building was vacant and the lot had 70 foot high piles of rubble on it. Today the CCGT focuses on "helping professionals and homeowners learn how green technology is cost-effective and good for the environment and people" (CityofChicago.org, 2006). The site is designed as a demonstration facility for several innovative stormwater technologies. The site uses four large water-storage cisterns to catch rainwater and use it for irrigation. It also makes use of native plants to minimize maintenance and water needs. Runoff is directed into bioswales which flow into an on-site wetland. The water conservation system retains over half of the rainwater that falls on the property. This system reduces total stormwater volume and flow rate, as well as improves water quality through on-site infiltration. The CCGT is a very important case study in stormwater management because it confirms that innovative technologies can be successfully used in cold climates.

By incorporating porous pavements, bioretention cells, and grassed swales into a parking lot design, the Florida Aquarium in Tampa, FL, was able to keep their entire stormwater volume on-site during small storm events (Davis, 2003). The water either infiltrated or evapotranspired which meant that no stormwater or its associated pollutants left the property. Implementing simple LID concepts can reduce pollutant loads as follows: ammonia (80-85%), nitrate (66-79%), suspended solids (91-92%), copper (81-94%), iron (92-94%), manganese (92-93%), lead (88-93%), and zinc (75-89%) (Davis, 2003).

Many applications of LID strategies have proven to be more cost-effective than traditional development. "According to the Center for Watershed Protection, traditional curbs, gutters, storm drain inlets, piping and detention basins can cost two to three times more than engineered grass swales and other techniques" (PWUD, 2006). A developer in North Little Rock, AR, designed the Gap Creek community as an environmentally sensitive land design. Comparing development under a conventional plan and a revised green plan, the developer reported several benefits of the green plan that resulted in a total economic benefit of more than $2.2 million in savings: higher lot yield, higher lot value, lower cost per lot, enhanced marketability, and added amenities (PWUD, 2006).

Sanitation District No. 1 (SD1) in Northern Kentucky provides a compelling example of stormwater management retrofit capabilities. SD1's facility is a proving ground for several innovative stormwater management techniques. In order to show their commitment to protecting local waterways, SD1 retrofitted their own administrative office with structural BMPs. In serving as a demonstration site for post-construction stormwater runoff control, the facility includes a vegetated roof, riparian zone restoration/preservation, wet and dry detention basins, a runoff storage cistern, porous pavements, oil/water separators, a stormwater pond and wetland, a biofiltration swale, and vegetated infiltration ditches (SD1, 2006). "The District will generate performance data on these controls that should prove extremely valuable in promoting the use of such cutting-edge practices throughout the community" (SD1, 2006).

Figure 7: Biofiltration Swale and Dry Detention Basin Retrofit (SD1, 2006). Sanitation District No. 1 in Fort Wright, Kentucky retrofitted their existing administrative office facility with numerous structural BMPs to serve as an example for the community.

2.4.2. Stormwater Technologies of Interest

This research will focus on nine stormwater management practices. In accordance with Value-Focused Thinking methodology, these nine management practices were not predetermined, but were identified in step 6 (alternative generation) of the VFT process. This step of the VFT process is more fully explained in Chapter 3. Infiltration BMPs are of specific interest to the decision makers because they are generally considered to be the best alternative stormwater technologies since they promote both stormwater volume reduction and water quality improvement. An infiltration BMP is designed to capture stormwater runoff and infiltrate that volume into the underlying soil. Secondary benefits of infiltration practices include increasing recharge of groundwater and preventing erosion. Some disadvantages of infiltration BMPs include potential contaminant migration to drinking water, poor performance in areas with poorly permeable soils, soil clogging due to sediment accumulation, and the need for frequent maintenance (EPA, 1999a). The nine management practices of interest appear below accompanied by a short description of each including characteristics, advantages, and disadvantages.

2.4.2.1 Infiltration Basin

An infiltration basin is an impoundment designed to collect stormwater and allow it to infiltrate into the ground over a period of time. Although it may hold water for a couple of days, it is not meant to be a permanent pool. Infiltration basins are generally used to treat runoff from large areas such as parking lots. This BMP has high pollutant removal efficiency. A well maintained basin can remove up to 75% of total suspended solids (TSS), 60-70% phosphorous, 55-60% nitrogen, 85-90% metals, and 90% bacteria (EPA, 2006a). In addition to removing pollutants, infiltration basins can help to restore or maintain pre-development hydrology. They also can be used as recreation areas when they are dry. Basins that do not drain within 72 hours may facilitate mosquito breeding and odor problems due to standing water. Slow draining basins may also be problematic by not being ready to receive runoff from the next storm (EPA, 1999a). Infiltration basins are relatively cost-effective practices because little infrastructure is needed when constructing them. The capital cost for a basin is around $2 per cubic foot of treated water (EPA, 2006a), while maintenance costs are estimated at 5 to 10 percent of construction costs. Regular maintenance is an important part of implementing infiltration basins. Poorly maintained basins have the potential to clog. Infiltration basins historically experienced high rates of failure due to clogging associated with poor design, construction, and maintenance (Debo and Reese, 2003).

Figure 8: Infiltration Basin Photo (EPA, 2006a). Infiltration basins collect stormwater runoff from impervious surfaces and remove pollutants through detention and filtration.

2.4.2.2 Infiltration Trench

An infiltration trench is a rock-filled trench lined with filter fabric that accepts runoff. The trench filters pollutants from the water as it infiltrates through the stones into the soil (EPA, 1999d). Infiltration trenches are meant to treat runoff from areas up to ten acres. They are not effective for larger areas because they cannot handle the associated peak storm flows. Typical pollutant removal efficiencies are 90% TSS, 60% nutrient, and 90% metals (EPA, 1999d). One advantage of this BMP is that it reduces the total volume of stormwater through groundwater recharge. Another advantage is that the narrow shape enables infiltration trenches to be adapted to many different types of sites (Debo and Reese, 2003: 863). As with all infiltration BMPs, the application of an infiltration trench must be carefully analyzed to determine the potential risk of groundwater contamination. The capital cost required to construct an infiltration trench is about $4 per cubic foot of treated water, while annual maintenance costs can range from 5-20% of the capital cost (EPA, 1999a). The primary maintenance goal for a proper functioning infiltration trench is to prevent the system from clogging. Trenches should be inspected after all major storm events in order to remove accumulated material (UFC, 2004). Pretreatment devices are an effective way to limit the amount of pollutant accumulation in a trench and to handle peak hydraulic flows.

Figure 9: Infiltration Trench Construction (PWUD, 2006). Infiltration trenches are first lined with filter fabric and are then back-filled with stone to capture pollutants as the water filters down to the soil.

2.4.2.3 Rain Garden

A rain garden, or bioretention cell, is a structural stormwater control measure that collects and temporarily stores runoff. This treatment unit removes pollutants by utilizing the filtration properties of soils as well as woody and herbaceous plants (Debo and Reese, 2003: 819). Runoff is conveyed as sheet flow to the rain garden where it ponds and slowly infiltrates (EPA, 1999c). These treatment units are usually planted with native wetland and prairie vegetation. Some rain gardens include an underdrain to prevent groundwater contamination, while others include an overflow drain to prevent flooding during large storms. Both types of drains usually connect to a municipal storm sewer system. Rain gardens remove pollutants through both physical and biological processes, including adsorption, filtration, plant uptake, microbial activity, decomposition, sedimentation, and volatilization (EPA, 1999c). Associated pollutant removal efficiencies are 90% TSS, 95% metals, 90% organics, 90% bacteria, and 75% nutrients (EPA, 1999c; Debo and Reese, 2003). Rain gardens not only provide localized stormwater control, but are also easy to plan and build, are aesthetically pleasing, incorporate existing natural site features, and preserve natural/native vegetation (PWUD, 2006). One drawback to these stormwater control measures is that they may need to be irrigated during dry periods; however, the use of native plants suited to the local conditions can prevent this requirement. As with other temporary ponding BMPs, inadequate maintenance of rain gardens can cause the system to clog leading to flooding, permanent ponding between rainfall events, or even growths of nuisance insect populations. Routine maintenance and inspections keep rain gardens functioning properly. Rain gardens can cost about $5.30 per cubic foot of treated water to construct with annual maintenance costs averaging around 6% of the capital cost (EPA, 1999a).

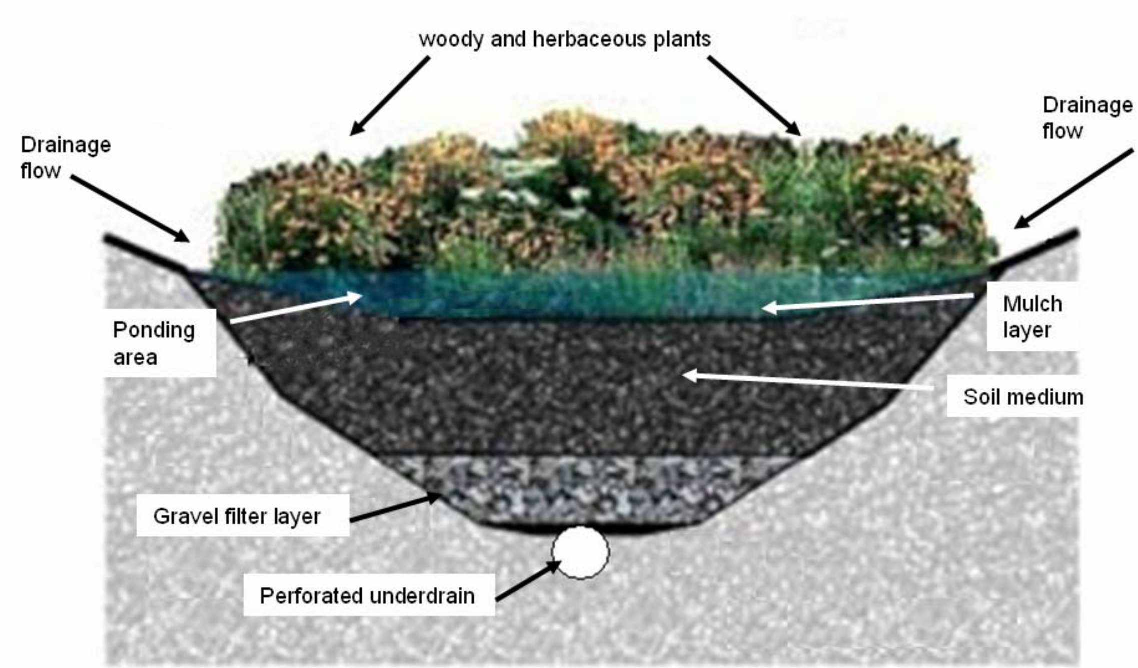

Figure 10: Rain Garden Cross-section.

2.4.2.4 Open Space

Open space design is incorporated into site planning by concentrating all impervious surfaces in one area while proving natural open spaces on another part of the site. Open space designs can reduce impervious cover, stormwater pollutants, construction costs, grading, and the loss of natural areas (EPA, 2006a). Implementing open space design can consist of simply preserving existing site features or potentially having to plant grasses, shrubs, and trees. Ideally, open space should be a native vegetation area rather than a manicured lawn. Manicured turf does not provide the same water quantity and quality benefits as native grasses due to reduced permeability. The capital cost of open space design is minimal when existing site features are utilized. Annual maintenance cost is also very low. Maintenance activities include trash collection, inspecting for invasive species, and any mowing or trimming that is required to maintain an acceptable appearance. In commercial or industrial areas, open space design can be incorporated into the site layout by replacing lawns with a mix of native prairie grasses and indigenous trees. Open space helps to improve downstream water quality by infiltrating stormwater runoff on site. Natural vegetation also reduces erosion and helps to filter sediment and other pollutants from the water.

2.4.2.5 Constructed Sand Filter

A sand filtration system, or sand filter, is a structural stormwater control that captures runoff and filters it through a bed of sand. Sand filters improve stormwater quality, but do little to reduce overall volume; therefore, they do not prevent downstream erosion or flooding. Sand filters usually have two treatment chambers (EPA, 1999f). The first one is a sedimentation basin where heavy sediments are removed. The second one is the filtration chamber which removes pollutants by filtering water through a bed of sand. Most sand filters pass treated water to a storm sewer system; however, some filters empty into surrounding soils if the soils are highly permeable. In areas where ground water contamination is a concern or surrounding soils have poor permeability, implementing a sand filter to treat stormwater is a better option than making use of an infiltration treatment measure. Sand filters take up very little space compared to other BMPs and can be easily implemented in a site retrofit. Sand filters do require routine maintenance to prevent clogging. They also may need to have the filter media replaced every 3-5 years to maintain their pollutant removal effectiveness (EPA, 1999f). Maintenance demands for sand filters are generally higher than for other BMPs, especially if the filter is located underground. Typical sand filter systems can remove 70-80% of total suspended solids, 40% of nutrients, 45% of metals, and 70% of petroleum products (Debo and Reese, 2003; EPA, 1999f). Costs for sand filters can vary greatly. The EPA estimates construction costs at $3-6 per cubic foot of treated water, while annual maintenance costs are 11-13% of the initial construction cost (1999a).

2.4.2.6 Grassed Swale

Grassed swales are generally considered to be low-cost alternatives to traditional stormwater conveyance systems. In fact, they can often greatly reduce or eliminate the need for curbs, gutters, and storm sewer systems (EPA, 1999h). A grassed swale is a shallow channel with a dense vegetative cover and a slight gradient leading runoff away from the stormwater source. Grassed swales reduce runoff flow rate, resulting in higher infiltration and pollutant removal rates. To encourage more effective infiltration and pollutant removal, native grasses and wildflowers should be selected over conventional turfgrasses (PWUD, 2006). Grassed swales are simple to design and can be used alone or in conjunction with other BMPs. They are ineffective in areas that are either too flat or too steep and can be susceptible to erosion during large storm events. Swales are also impractical in developments where space is limited. Pollutant removal rates can vary greatly subject to the local conditions and design configurations (Debo and Reese, 2003). A properly constructed and sited grassed swale is effective at removing metals (65%), TSS (81%), and hydrocarbons (62%) (EPA, 1999h); however, removal efficiency of nutrients is low. The EPA states that the useful life of a vegetated swale is directly related to its frequency of maintenance (1999h). Maintenance includes clearing out trash and other debris, preserving a dense and healthy grass cover, watering during dry spells, and cleaning out accumulated sediment. Constructing a grassed swale can cost as little as $0.50 per cubic foot of treated water while annual maintenance cost is about 5-7% of the construction cost (EPA, 1999a). Construction costs can vary depending on initial site conditions.

Figure 11: Grassed Swale Photo (EPA, 2006a). Grassed swales can be used along roadsides, parking lots, and buildings to collect and treat stormwater runoff.

2.4.2.7 Vegetated Filter Strip

Filter strips are bands of dense vegetation planted downstream of a runoff source (UFC, 2004). The use of a filter strip is limited to gently sloping areas where channelized flow is not likely to develop. They can treat runoff from roads, parking lots, roofs, construction sites, and other impervious surfaces. They slow runoff, filtering out sediment and other pollutants. While a grassed swale collects runoff into a concentrated channel, a vegetated filter strip works most effectively when runoff travels across it in an even sheet flow. A properly functioning filter strip can reduce total runoff volume by 40% (PWUD, 2006); however, the infiltration rate of runoff is drastically reduced if sheet flow is not maintained (EPA, 2006a). Concentrated flows often receive little or no treatment. One significant drawback to using filter strips for stormwater management is that they require a large amount of space, potentially equaling the impervious area they treat. Pollutant removal effectiveness varies depending on the type of vegetation used and the size of the treatment surface. Filter strips made with porous media can have sediment and pollutant removal rates as high as 98% (PWUD, 2006). More common removal rates are 80% for TSS, 50% for metals, and 30% for nutrients (EPA, 2006a). Maintenance for a filter strip is relatively low. The basic activities include removing trash and other debris, maintaining a dense vegetative cover, and controlling erosion from concentrated flows. Filter strips may require very little monetary expenditures if an open grassy area already exists near the runoff source. New filter strips can cost up to $1.30 per cubic foot of treated water based on how they are installed (seed versus sod); maintenance costs are usually under 5% of the construction cost(EPA, 1999a).

Figure 12: Vegetated Filter Strip (OH NRCS, 2007). In this photo, a well-established, native-grass filter strip serves as a buffer between a farm field and a stream. The filter strip helps to prevent stream bank erosion and water quality degradation by reducing the runoff flow rate and filtering pollutants.

2.5. Existing BMP Selection

Throughout the published literature there is no universally accepted method for selecting structural best management practices. However, from reviewing the numerous selection guidelines that are available, it is evident that several key factors are consistent across selection methodologies. The major factors to consider include the following: watershed characteristics, land use, climate factors, terrain factors, stormwater treatment suitability, physical feasibility, community and environmental factors, and stormwater management capability. The most complete set of selection guidelines are published by the Maryland Department of the Environment (Department of the Environment, 2000) and the Center for Watershed Protection (Center for Watershed Protection, 2006). Both organizations developed matrices to evaluate BMPs. The matrices developed are not necessarily exhaustive and are meant as screening tools rather than mandates. A user of the matrices should keep in mind that a matrix cannot replace technical understanding of how rainfall, surface water hydrology, soils, and vegetation interrelate. Although very useful for screening alternatives, neither set of matrices offers a way to score or rank BMPs against each other. An example of a physical feasibility matrix is below.

Table 2: Physical Feasibility Factors Matrix for BMP Selection (Department of the Environment, 2000).

CODE	BMP LIST	SOILS	WATER TABLE	DRAINAGE AREA (Acres)	SLOPE RESTRICT.	HEAD (Ft)	ULTRA URBAN
P-1	Micropool ED	"A" Soils May Require Pond Liner "B" Soils May Require Testing	4 Feet[1] If Hotspot Or Aquifer	10 Min[2]	None	6 to 8 Ft	Not Practical
P-2	Wet Pond			25 Min[2]			
P-3	Wet ED Pond						
P-4	Multiple Pond						
P-5	Pocket Pond	OK	Below WT	5 Max[3]		4 Ft	OK
W-1	Shallow Wetland	"A" Soils May Require Liner	4 Feet[1] If Hotspot Or Aquifer	25 Min	None	3 to 5 Ft	Not Practical
W-2	ED Wetland						
W-3	Pond/Wetland						
W-4	Pocket Wetland	OK	Below WT	5 Max		2 To 3 Ft	Depends
I-1	Infiltration Trench	$f \geq 0.52$ Inch/Hr	4 Feet[1]	5 Max	Installed in No More Than 15% Slopes	1 Ft	Depends
I-2	Infiltration Basin			10 Max		3 Ft	Not Practical
F-1	Surface Sand Filter	OK	2 Feet	10 Max [3]	None	5 Ft	Depends
F-2	Underground SF			2 Max [3]		5 to 7ft	OK
F-3	Perimeter SF			2 Max [3]		2 to 3 Ft	
F-4	Organic Filter			5 Max[3]		2 to 4 Ft	
F-5	Pocket SF			5 Max [3]		2 to 5 Ft	
F-6	Bioretention	Made Soil				5 Ft	
O-1	Dry Swale	Made Soil	2 Feet	5 Max	4% Max Cross-slope	3 to 5 Ft	Not Practical
O-2	Wet Swale	OK	Below WT	5 Max		1 Ft	

Notes: OK= not restricted, WT= water table

1 **Four foot separation distance is maintained to the seasonally high water table (2 feet on Lower Eastern Shore).**

2 **Unless adequate water balance and anti-clogging device installed**

3 **Drainage area can be larger in some instances**

2.6. Decision Analysis

Decision analysis is the discipline for systematically making complex decisions considering alternatives, uncertain variables, and preferences in order to give insight to decision makers (Knighton, 2006). Several benefits of decision analysis include increased objectivity, clarified thinking, improved communication, repeatable decisions, and logical reasoning. Decision analysis is very applicable for “decisions where there are multiple competing objectives that require consideration of tradeoffs among these objectives” (Kirkwood, 1997: 1). An objective is simply “a statement of something that one desires to achieve” (Keeney, 1992: 34). Decision analysis offers a structured approach to handle decisions objectively and strategically. This is done by quantifying and analyzing all important components of the decision. Kirkwood proposes a five step strategic approach to decision making:

1- Specify objectives and scales for measuring achievement with respect to these objectives.
2- Develop alternatives that potentially might achieve the objectives.
3- Determine how well each alternative achieves each objective.
4- Consider tradeoffs among objectives.
5- Select the alternative that, on balance, best achieves the objectives, taking into account uncertainties. (1997:3)

There are two main schools of thought on how to perform decision analysis: alternative-focused thinking and value-focused thinking. An explanation of both methods follows.

2.6.1. Alternative-Focused Thinking

Decision making often begins with the identification of several alternatives and then focuses on making a choice among them. This is known as alternative-focused thinking (AFT) and often leads to choosing the “best of the worst.” Unfortunately, this decision making attitude is prevalent throughout society today, most likely because focusing only on obvious alternatives is the easy way out of making complex decisions (Keeney, 1992: 6). AFT consists of five major activities: recognizing a decision problem, identifying alternatives, specifying values, evaluating alternatives, and selecting an alternative (Keeney, 1992: 49). The first step is usually reactive in which someone is simply responding to a problem that has arisen. Identifying alternatives often consists of looking at a list of known options. Once alternatives have been identified, the decision maker's values are specified. These values are then used to evaluate the alternatives and select the best one. One benefit of AFT is that without having to develop new alternatives, the entire process can happen relatively quickly. This benefit is also a drawback to the approach. In only working with known alternatives, AFT does not consider other possibilities which might provide a better solution to the problem. There is often no scientific approach to generating the list of alternatives other than simply choosing the obvious choices that are readily available or familiar to the decision maker. Keeney suggests there is a better way to perform decision making: value-focused thinking.

2.6.2. Value-Focused Thinking

Value-focused thinking (VFT) is a multi-objective decision analysis method. "It consists of two activities: first deciding what you want and then figuring out how to get it" (Keeney, 1992: 4). VFT involves thinking about what is important to the decision maker (i.e. values) and then working to make the ideal option a reality. Values are formed from many sources including ethics, desired traits, characteristics of consequences that matter, guidelines for action, priorities, value tradeoffs, and attitudes toward risk (Keeney, 1992: 7). Thinking about values brings many benefits to the decision analysis process. The figure below shows some of these advantages.

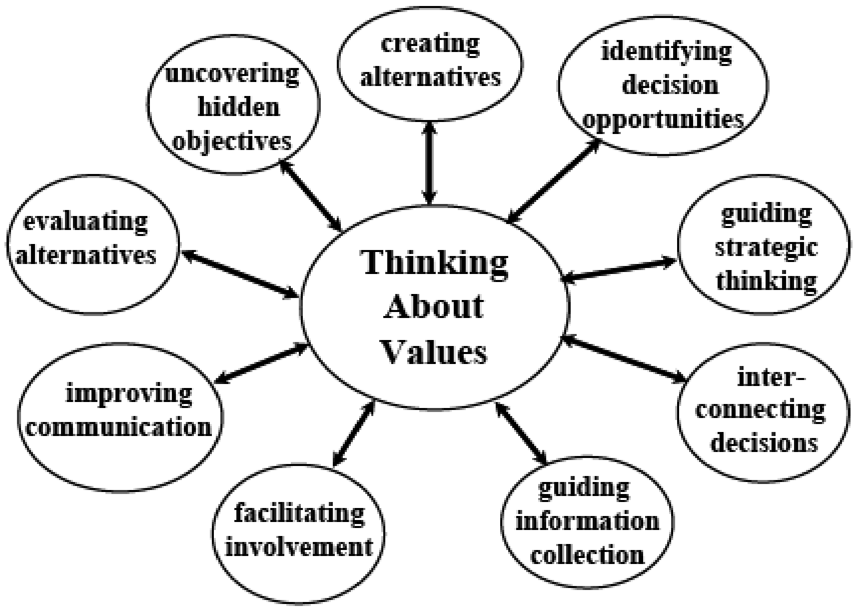

Figure 13: Benefits of Value-Focused Thinking (Keeney, 1992: 24). Thinking about values contributes many advantages to the decision analysis process that are otherwise missed in an alternative-focused thinking approach to decision making.

VFT is a "structured method for incorporating the information, opinions, and preferences of the various relevant people into the decision making process" (Kirkwood, 1997). It relies on specific objectives, evaluation considerations, evaluation measures, and value hierarchies. Similarly to AFT, VFT consists of five major activities: recognizing a decision problem, specifying values, creating alternatives, evaluating alternatives, and selecting alternatives (Keeney, 1992: 48). These are actually the same five steps of AFT; however, the order for the second and third steps is reversed. In VFT alternatives are only identified once the decision maker's values have been specified.

Keeney contends that this is a better way to make decisions because values are the driving force for our decision making; thus, “they should be the basis for the time and effort we spend thinking about decisions” (1992: 3). When an alternative is chosen using VFT, it is the alternative that creates the most value for the decision maker. Rather than choosing among known alternatives, VFT can create new alternatives based on the decision maker’s stated values and objectives. These additional alternatives are often better than the original options.

2.6.3. Ten Step VFT Process

Shoviak broke down Keeney’s five major activities into a ten step VFT process: identifying a problem, creating a value hierarchy, developing evaluation measures, creating single dimensional value functions, weighting the value hierarchy, generating alternatives, scoring the alternatives, conducting deterministic analysis, conducting sensitivity analysis, and providing conclusions and recommendations (Shoviak, 2001). These steps are further explained below.

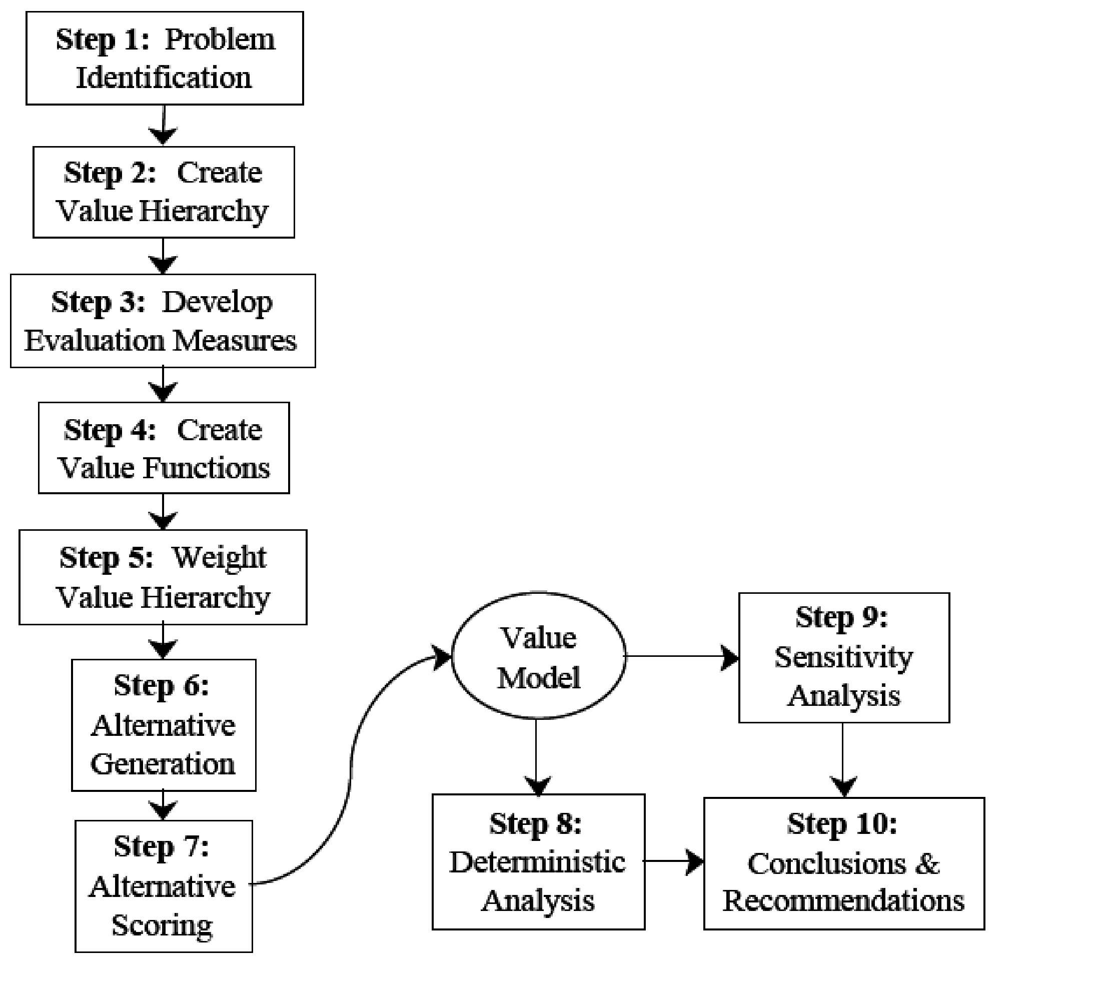

Figure 14: Value-Focused Thinking 10 Step Process (Shoviak, 2001: 63).

2.6.3.1 Problem Identification

The VFT process begins with the identification of an appropriate problem. Although this step may sound relatively simple, it is often not given enough consideration. Defining a problem scopes the entire decision analysis process. If the wrong problem is identified, decision makers may waste valuable resources and receive nothing in return. Many times the symptoms of problems are identified rather than the cause.

2.6.3.2 Create Value Hierarchy

In value-focused thinking, the decision context is captured in a value structure. A "value structure encompasses the entire set of evaluation considerations, objectives, and evaluation measures for a particular decision analysis" (Kirkwood, 1997:12). An evaluation consideration is any concern that is taken into account when analyzing the decision process. An objective describes the "preferred direction of movement" of an evaluation consideration (Kirkwood, 1997:12). An evaluation measure is a scale used to assess how well an alternative meets an objective. Kirkwood says that when a value structure is organized in a hierarchical structure it is called a value hierarchy. Figure 15 below shows a sample value hierarchy.

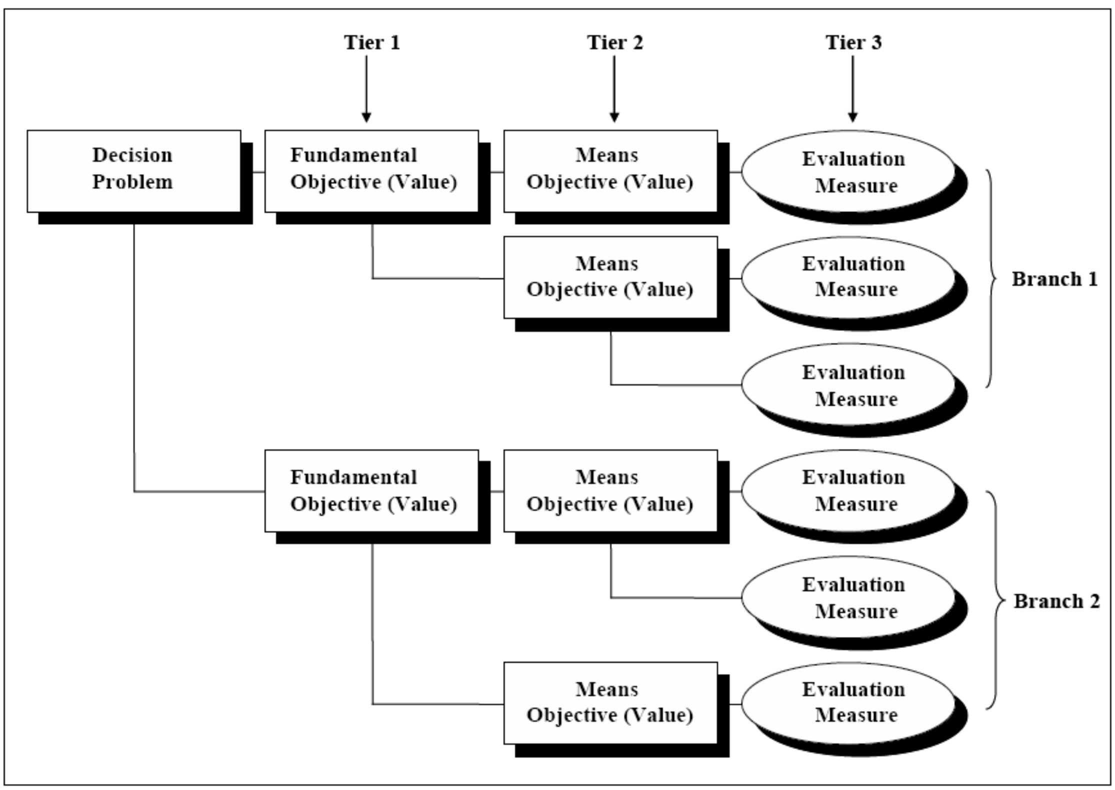

Figure 15: Example of a Generic Value Hierarchy (Jeoun, 2005:32).

In the figure above, the box in the top left is the overall decision to be made. The rest of the hierarchy is divided into tiers and branches. A tier consists of all the evaluation considerations that are the same distance from the top of the hierarchy (Kirkwood, 1997:13). Branches are composed of all the objectives and evaluation measures that derive from a single evaluation consideration (Bulson, 2006). A value hierarchy should have as many tiers and branches as necessary in order to capture all pertinent information to the decision problem.

A value hierarchy has five desirable properties: completeness, nonredundancy, independence, operability, and small size (Kirkwood, 1997:16). A complete value hierarchy encompasses all concerns and values that are needed to accurately evaluate the decision problem. A nonredundant value hierarchy is one in which no two evaluation considerations have common characteristics. To be independent, the score assigned to each evaluation measure must not depend on the score of any other evaluation measure. Operability refers to the value hierarchy being easily understood by the decision maker. Small size facilitates operability and requires fewer resources to score evaluation measures.

2.6.3.3 Develop Evaluation Measures

In order to make a value hierarchy a quantitative decision tool, evaluation measures must be applied to the lowest level values. Evaluation measures specify the degree of attainment of objectives by providing "an unambiguous rating of how well an alternative does with respect to each objective" (Kirkwood, 1997:24). The scale used to score an evaluation measure can be natural or constructed and direct or proxy. A natural scale is one that is easily understood by all people without further explanation, such as miles to measure distance. A constructed scale is created for a specific problem, such as the scoring system for figure skating competition. A direct scale directly measures the score of an objective while a proxy scale measures the degree of performance of an associated objective (Kirkwood, 1997:24). Kirkwood says profit in dollars is a natural scale and gross national product as a measure of economic well-being is a proxy scale.

2.6.3.4 Create Value Functions

Step four in the ten step process is creating single dimensional value functions (SDVF). Each evaluation measure has specific units. Because these units are normally different from each other, a SDVF is used to convert each measurement scale to common units. These normalized scales have units of "value" and range from 0 to 1. The least preferred score for each evaluation measure will be awarded a value of zero while the most preferred score will be awarded a value of one. The value for each intermediate score is determined by the shape of the SDVF. SDVFs are always either monotonically increasing or monotonically decreasing, which means higher levels of a measure are always either more preferred or less preferred (Kirkwood, 1997). A SDVF can be continuous or discrete. A discrete SDVF can be binary or can have several intermediate bins. A continuous SDVF can be linear, piece-wise linear, or exponential. The type of value function used should be chosen to most accurately reflect the decision maker's preference attitude. See Figure 16 for examples of commonly used SDVFs.

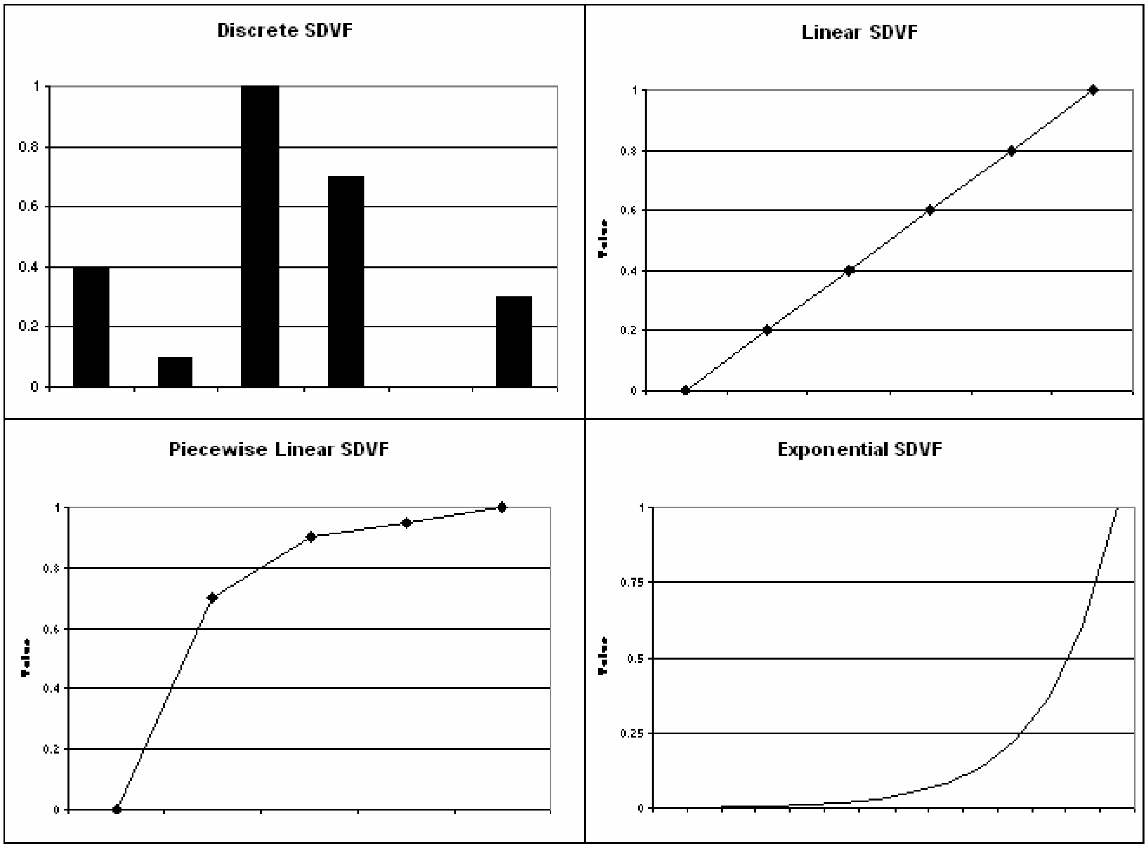

Figure 16: Example of Generic Single Dimensional Value Functions.

2.6.3.5 Weight Value Hierarchy

In decision problems, it is very unlikely that every value in the hierarchy is equally important to the decision maker. As a result, each evaluation measure must be weighted to reflect its relative importance. Methods for determining weights will be discussed in Chapter 3. Weighting the hierarchy can be accomplished in two ways: global weighting or local weighting. Global weighting is accomplished by applying weights to each evaluation measure at the bottom of the hierarchy. The weights for all of the evaluation measures taken together must sum to 1. The weights of objectives on upper tiers are determined by summing the weights of the measures, or objectives, directly below. Global weighting makes it easy to see the relative importance of each measure compared to the others; however, global weighting becomes increasingly complex as the number of evaluation measures increase.

Local weights are assigned to the objectives across a tier within a branch. The weights of each tier within a branch must sum to 1. This weighting process begins at the top of the hierarchy and moves down. Global weights can be determined by multiplying the local weight of a measure by the local weight of the objectives directly above it.

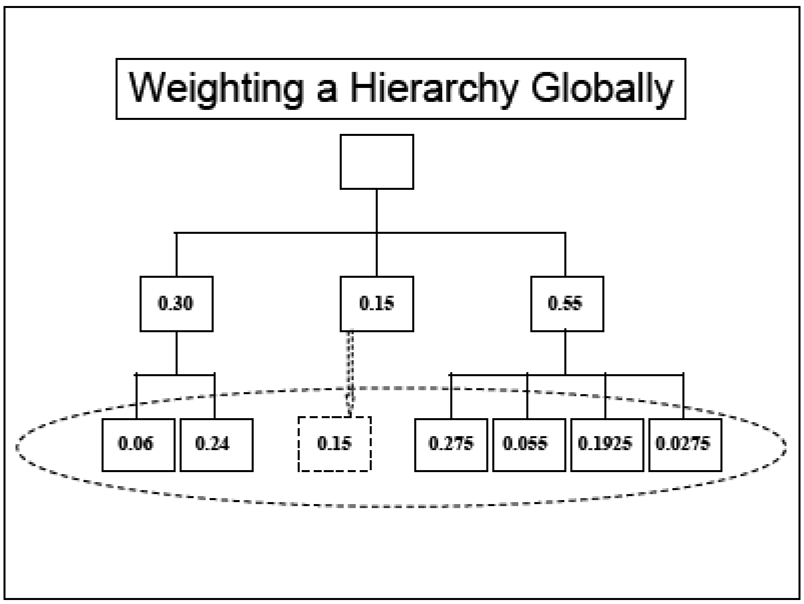

Figure 17: Example of Global Weighting (Knighton, 2006).

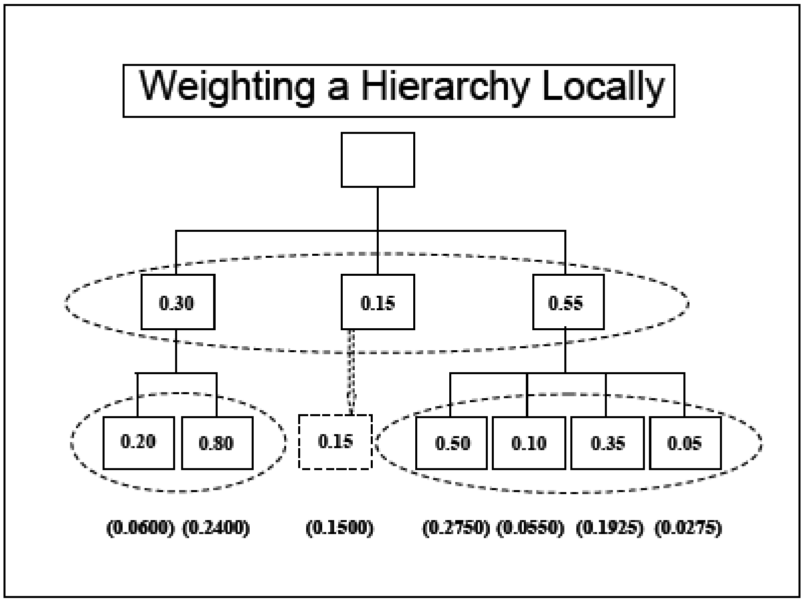

Figure 18: Example of Local Weighting (Knighton, 2006). Global weights for the evaluation measures are shown at the bottom in parentheses.

2.6.3.6 Alternative Generation

A preliminary list of alternatives is usually provided by the decision maker or another person involved with the decision problem. The list can often include only the obvious alternatives, or alternatives that are all closely related due to the effects of being "anchored" in one mindset (Keeney, 1992). If there are too many alternatives to perform a thorough analysis, a screening process must be used to identify a smaller number of alternatives (Kirkwood, 1997:44). If there are too few alternatives, or perhaps no good alternatives on the list, new options must be created. One way to create new alternatives is to think about individual values in the hierarchy and identify alternatives that are either good or bad based only on that value. In this way, several new alternatives can be created that may score well across the entire hierarchy.

2.6.3.7 Alternative Scoring

In step 7, each alternative is scored based on the identified evaluation measures and single dimensional value functions. In order to complete this step, data must be collected for each alternative across each evaluation measure. This data can be solicited from published literature, a subject matter expert, or even the decision maker.

2.6.3.8 Deterministic Analysis

In order to determine an overall score for each alternative, an additive value function is used. The form of this function is a weighted sum of single dimensional value functions over each evaluation measure (equation shown below) (Knighton, 2006).

$$\mathrm{v(x)} = \sum_{i=1}^{n} w_i v_i(x_i) \tag{1}$$

Where:

$v(x)$ = overall score for alternative x

w_i = global weight for evaluation measure i

$v_i(x_i)$ = value score for alternative x from SDVF for measure i

x_i = score for alternative x on measure i

n = total number of evaluation measures

Once each alternative has a final score, they can be ranked in relation to how well each one achieves the overall decision objective. Total value scores only provide information on the rank of each alternative. Total scores cannot be used to determine how much better one alternative is over another one.

2.6.3.9 Sensitivity Analysis

Sensitivity analysis involves examining how the final value scores and ranking of alternatives change in relation to changes in weights. The weights are altered systematically by changing the weight of one objective, and adjusting the other weights to ensure they sum to one and also maintain the proportionality of the other weights to each other (Shoviak, 2001:61). Sensitivity is important to decision makers because it tells them whether they should expend more resources on further refining their inputted data or any uncertainty that may be a part of the problem. It also helps a decision maker to rethink their assigned weights in order to be more confident in the final decision model.

2.6.3.10 Conclusions and Recommendations

Step 10 simply entails presenting the results of the decision analysis process to the decision maker. The results of the deterministic and sensitivity analysis should be presented as well as any other lessons that were garnered as a result of performing an in depth analysis of the decision problem.

3. Methodology

3.1. Overview

Two methodologies are used in this research to answer the five research questions listed in Chapter 1: literature review and value-focused thinking (VFT). The Literature Review, recorded in Chapter 2, answers research questions 1, 2, and 3:

1. What environmental and economic concerns are associated with stormwater runoff in developed areas?
2. What innovative stormwater management technologies have been used successfully in the past?
3. What features, advantages, and disadvantages exist for specific innovative stormwater management technologies?

Performing a VFT analysis answers research questions 4 and 5:

4. What are Air Force decision makers' values when selecting stormwater management strategies?
5. Is Value-Focused Thinking an appropriate decision making methodology for selecting stormwater management technologies for use on Air Force installations?

Chapters 3, 4, and 5 fully explain the VFT process and show how it is utilized to develop a decision model to aid Air Force decision makers in evaluating and selecting appropriate stormwater management control measures. As stated in the literature review, the VFT process consists of 10 steps. This chapter covers the first six steps: identify the problem, create value hierarchy, develop evaluation measures, create single dimensional value functions, weight value hierarchy, and generate alternatives (Shoviak, 2001). Chapter 4 discusses the model analysis and Chapter 5 closes this work with conclusions and recommendations.

3.2. Step One: Problem Identification

The Air Force Center for Environmental Excellence (AFCEE) has an ongoing interest in learning how to better control the quantity and quality of stormwater runoff on Air Force bases. In 2006, Bulson completed research for AFCEE concerning the practicality of installing porous pavements on military installations (Bulson, 2006). AFCEE wanted to learn more about other innovative stormwater management technologies that are available for use. In addition, a systematic decision making model does not exist on how to evaluate and select stormwater management technologies for specific locations.

The Air Force Institute of Technology (AFIT) performs a significant amount of research in sustainable development. To apply some of this research to its own activities, AFIT is interested in exploring how to handle stormwater generated from the new classroom facility that is currently under construction. The VFT model developed in this research is tailored to evaluating stormwater best management practices at AFIT. Applying the VFT model to the AFIT facility serves as a proof of concept for how the model can be implemented at other locations. The decision maker for this problem was a team of two instructors from the AFIT Civil Engineer and Services School. One of the instructors is the stormwater course director and the other is one of the environmental course directors. These two instructors are knowledgeable about stormwater management issues across the Air Force as well as at AFIT. These two instructors are appropriate decision makers for this situation for two reasons. The first reason is that they teach civil engineers from throughout the Air Force about stormwater management. They can incorporate innovative stormwater management technologies into their curriculum so that students are able to apply these concepts once back at their daily job. The second reason for selecting them as the decision making team is that they often act in a consulting role to several agencies in the Air Force. Agencies that have a stormwater problem will contact the AFIT Civil Engineer School to seek answers. The instructors can then implement the VFT model to address their needs.

3.3. Step Two: Create Value Hierarchy

The value hierarchy in a decision problem is the "tree-like" structure used to capture the decision maker's "evaluation considerations, objectives, and evaluation measures" (Kirkwood, 1997: 12). The first step in creating a hierarchy is to identify the overall goal. This goal is taken from the problem identification. The overall goal of this decision analysis process, occupying the top box of the hierarchy, is identifying the best stormwater management technology. The rest of the hierarchy is created by soliciting information from the decision maker about what they think is important to the decision situation. To begin this process, I held a meeting with the two decision makers and asked them what they think is important when choosing a stormwater control measure. The set of values was then divided into groups of similar values. As explained in Chapter 2, these groups formed the branches of the hierarchy. Some values were eliminated due to redundancy. Some values were broken down further into multiple values. Once all values were sufficiently defined, an overall objective for each branch was identified. The three objectives, forming the first tier under the overall goal, are *Construction, Operations and Maintenance*, and *Performance*.

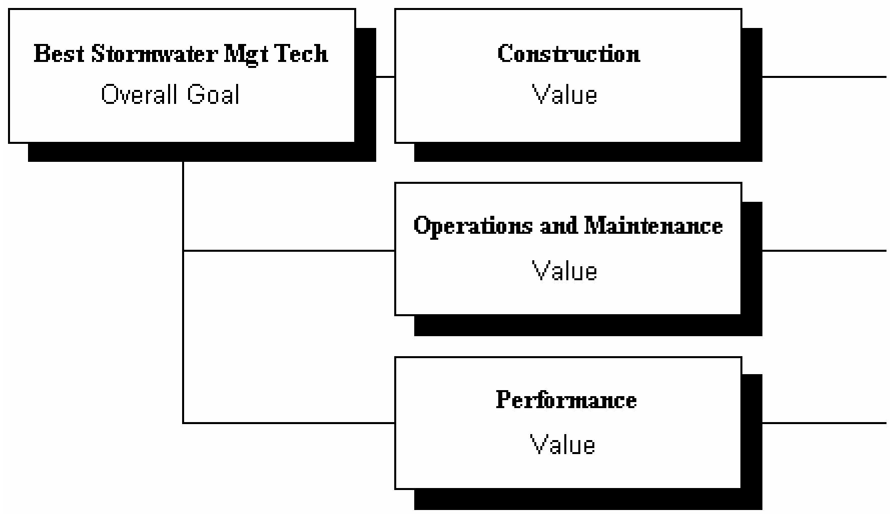

Figure 19: Overall Goal and First Tier of Value Hierarchy

3.3.1. Construction

The *Construction* objective captures the decision maker's values concerning the physical placement and actual construction of a selected stormwater management technology. This objective is broken down further into five values: disturbs natural site features, footprint, installation burden, past use in local area, and support for the Air Force Sustainable Development Policy Letter. *Disturbs natural site features* refers to whether or not the existing natural features are preserved or destroyed when constructing a particular stormwater control measure. It includes natural resource preservation, historical and cultural site preservation, and endangered or threatened species protection. This value is very site specific and is not simply concerned with the quantity of site features, but also the quality of site features. For example, digging up a parking lot and replacing it with a grass field would be a positive action, but filling in a wetland and replacing it with a grass field would be a negative action. *Footprint* refers to the amount of land the stormwater technology occupies. Physical size impacts the possibility of future expansion as well as the feasibility of siting the management practice of interest in a specific location. *Installation Burden* captures the overall ease of constructing a particular management practice. It includes factors such as estimated installation time, required equipment, and intensity of required labor. *Past use in Local Area* captures the degree to which the stormwater control practice has been successfully implemented in the area, as well as the level of expertise that exists in installation and maintenance. *Support for the Air Force Sustainable Development Policy Letter* helps to determine if the particular practice is meeting the Air Force's goals of implementing sustainable development wherever and whenever, consistent with budget and mission requirements. Stormwater best management practices can help to protect and conserve water by reducing, controlling, or treating site runoff. Overall construction cost is not included here in the value hierarchy. Because of independence issues with other values, capital cost will be included in this analysis by calculating an overall value ratio for each alternative at the end.

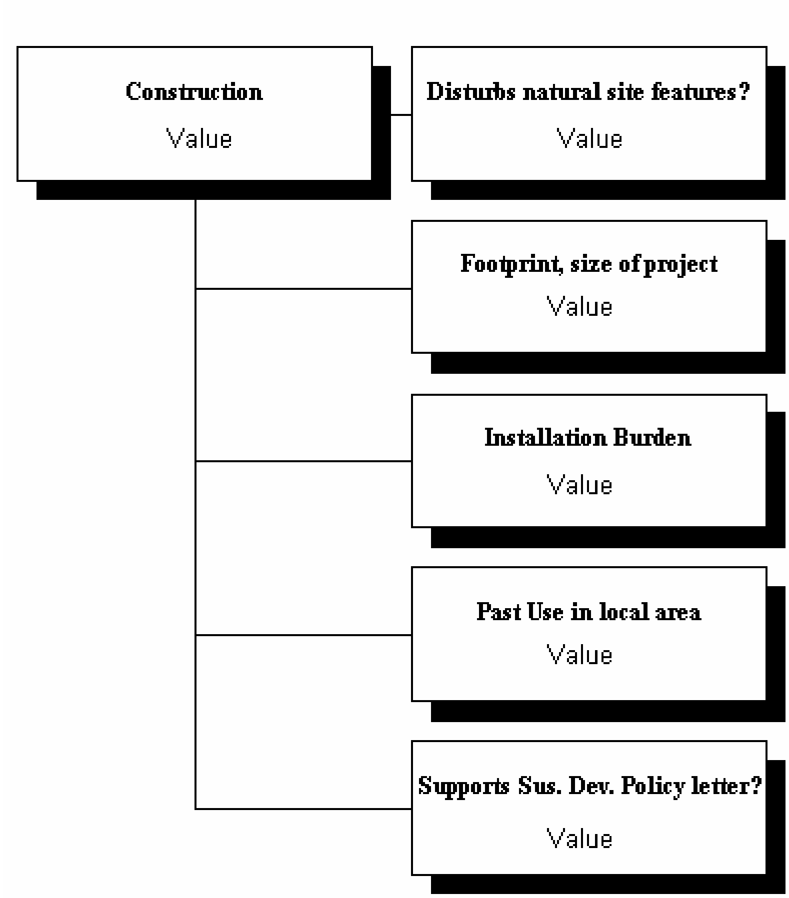

Figure 20: Construction Value broken down into its five lower level values.

3.3.2. Operations and Maintenance

The *Operations and Maintenance* objective refers to the decision maker's desire to implement a stormwater management strategy that does not have an unreasonable maintenance demand. With smaller budgets and fewer personnel available throughout civil engineer squadrons in the Air Force, maintenance activities should be minimized to save money and labor hours. *Annual Maintenance Cost* refers to the total estimated cost of maintaining each control measure for one year. *Simplicity of Maintenance* captures the overall intensity of maintenance activities. Because civil engineer personnel often have more work assigned than they can accomplish, stormwater control measures with labor intensive maintenance demands may not be maintained well enough to continue performing effectively. The simpler the maintenance, the more likely it will be accomplished correctly and the better the management practice will function. Independence is not a concern for these two values because of the definition of *Simplicity of Maintenance*. *Simplicity of Maintenance* does not affect the annual cost because it is simply a measure of how likely it is that the maintenance will be completed.

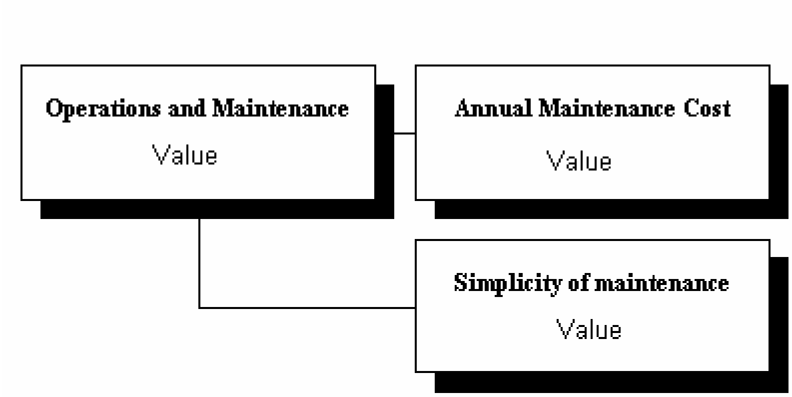

Figure 21: Operations and Maintenance value broken down into its lower level values.

3.3.3. Performance

As one of the members of the decision making team said, "the *Performance* objective is the major reason for even considering alternative stormwater management technologies." If a control measure does not perform as intended, then there is no point in spending the time, resources, or money in installing and maintaining it. The *Performance* objective refers to how effectively a management practice treats the volume and quality of stormwater runoff. *Performance* is broken down into three lower tier values of native vegetation, treatment effectiveness, and volume reduction. *Native vegetation* refers to whether or not the management practice can be constructed using vegetation native to the local area. Native vegetation provides habitat for local wildlife.

It also requires less maintenance than non-native species as it can survive local climate changes without continuous care. Unlike many non-native, invasive species, native vegetation does not present a danger to the health of other plant life in the area.

Treatment Effectiveness refers to how well a management practice removes stormwater pollutants. This value is broken down further into *Metals Removal*, *Nutrient Removal*, *POL Removal*, and *TSS Removal*. POL stands for petroleum, oil, and lubricant pollutants, and TSS stands for total suspended solids. The third value under *Performance* is *Volume Reduction*. Volume reduction refers to the ability of a particular stormwater control measure to reduce the overall volume of runoff produced on a particular site. This value represents a pollution prevention ethic. If runoff volume is reduced on-site, then it cannot pick up pollutants and deposit them downstream.

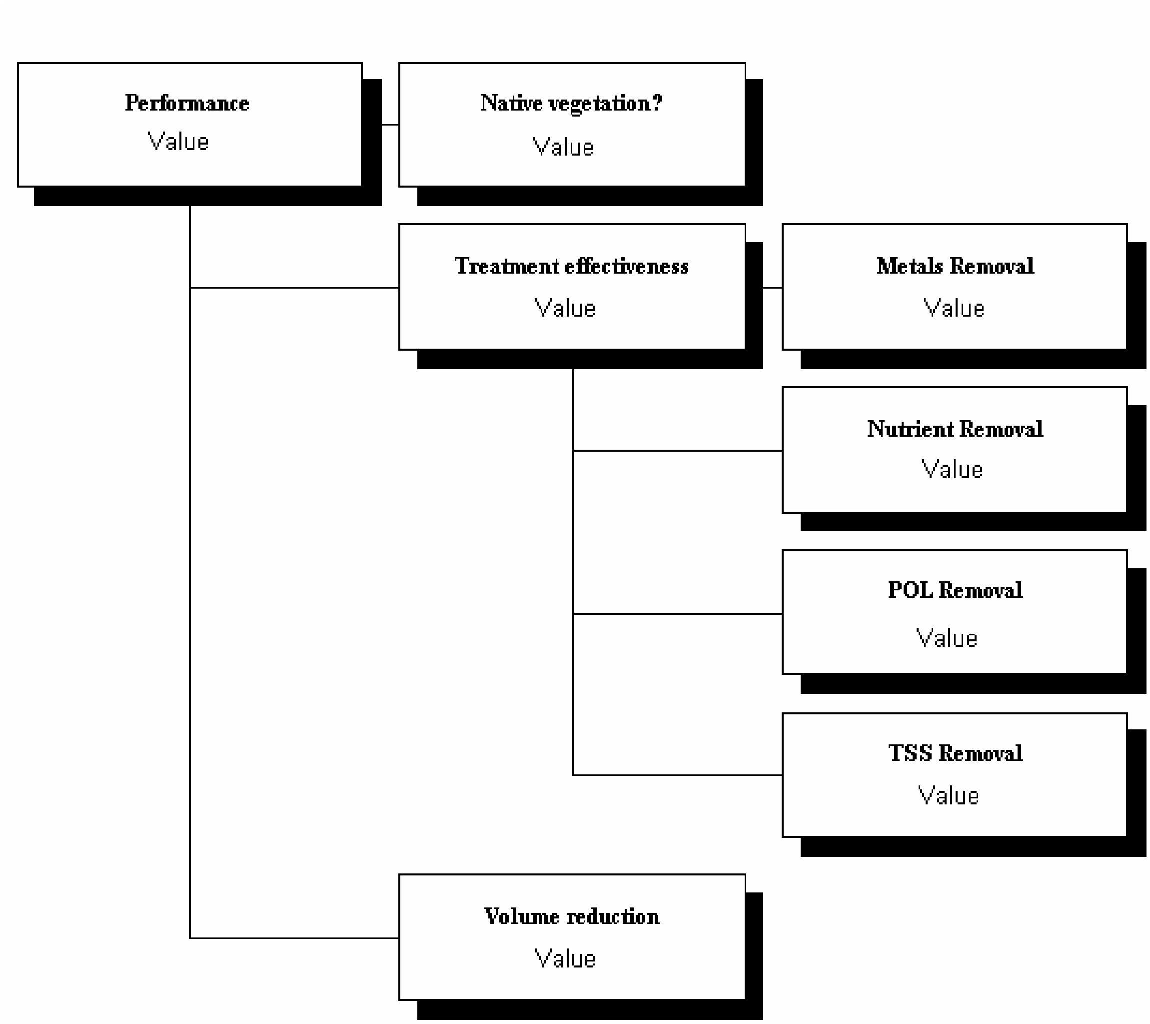

Figure 22: Performance value broken down into its lower level values.

3.4. Step Three: Develop Evaluation Measures

The value hierarchy developed in step two of the VFT process provides a valuable tool to qualitatively analyze a stormwater decision problem. However, to achieve the quantitative analysis benefits associated with VFT, it is necessary to develop evaluation measures for each of the lowest level values in the hierarchy. As stated in Chapter 2, evaluation measures specify the degree of attainment of objectives by providing "an unambiguous rating of how well an alternative does with respect to each objective" (Kirkwood, 1997:24). The thirteen lowest tier values and their associated evaluation measures are listed in the table below. The footprint evaluation measure is the only one that needs clarification. "% of impervious area" refers to the size of the management practice as a function of the size of the impervious area. For instance, control measure A may need to be sized at 10% of the impervious area from which it treats runoff. This means that if the treatment area is 1000 square feet, control measure A would take up 100 square feet. The complete value hierarchy with corresponding evaluation measures is shown in Figure 23.

Table 3: Evaluation Measures

Value	**Evaluation Measure**	**Categories (if applicable)**
Disturbs natural site features	Categorical	Yes/No
Footprint	% of impervious area	
Installation burden	Categorical	High/Medium/Low/None
Past use in local area	Categorical	None/Limited/Moderate/Extensive
Supports Sustainable Development Policy Letter	Categorical	Yes/No
Annual Maintenance Cost	Dollars, $	
Simplicity of maintenance	Categorical	Easy/Moderate/Difficult
Native Vegetation	Categorical	Yes/No
Metals Removal	% metals removed	
Nutrient Removal	% nutrients removed	
POL Removal	% POL removed	
TSS Removal	% TSS removed	
Volume Reduction	% volume reduction	

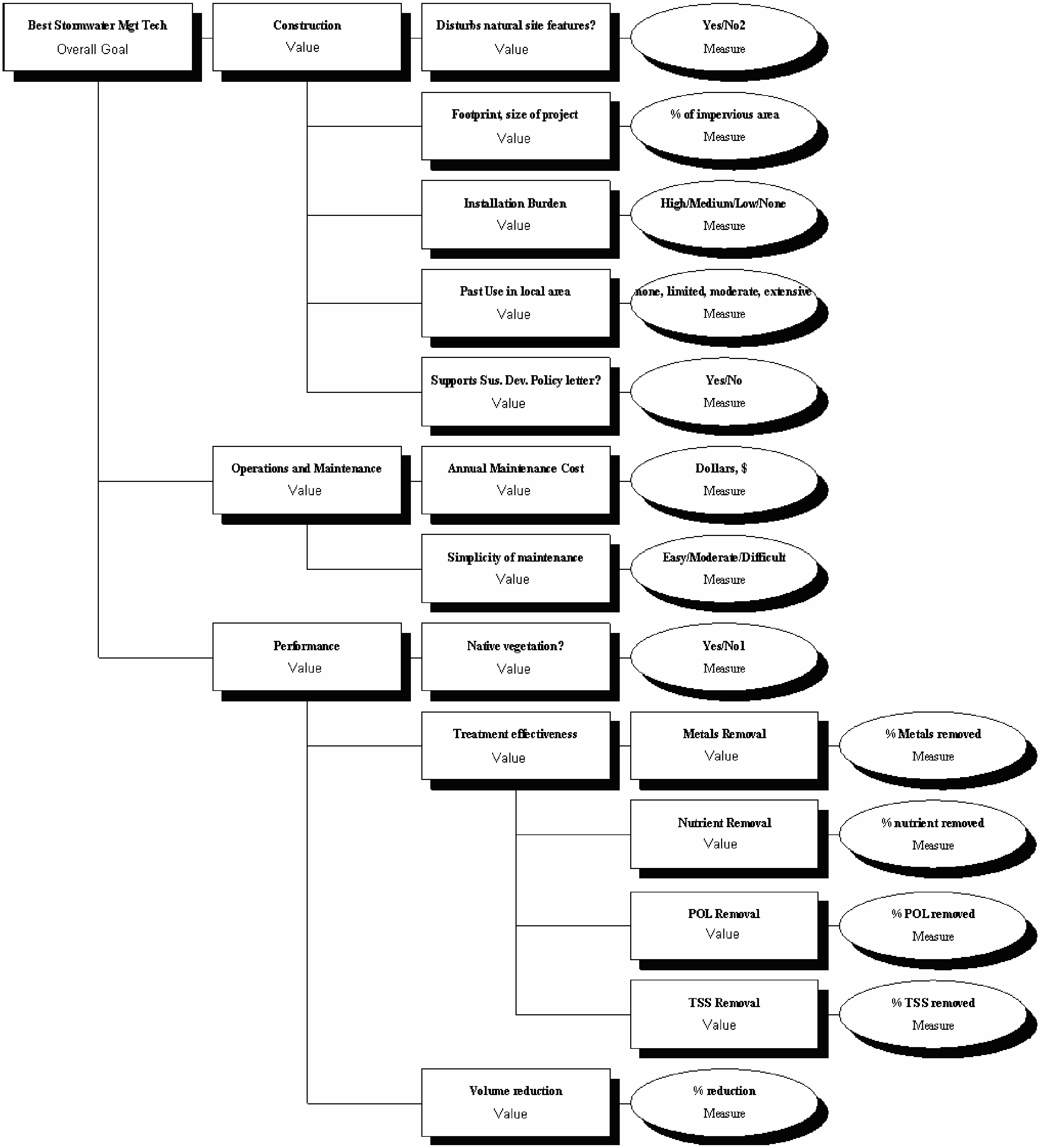

Figure 23: Overall Value Hierarchy

3.5. Step Four: Create Single Dimensional Value Functions

The purpose of single dimensional value functions (SDVFs) is to convert the scores for each evaluation measure into similar units. These units are called value and can range from 0 to 1, where 0 is least preferred and 1 is most preferred. Evaluation measures with categorical scales or only a few possible scoring levels, should make use of a discrete SDVF. A continuous SDVF is used when an infinite number of scoring levels is possible. Examples of discrete and continuous SDVFs were shown in Chapter 2. In this research, six of the seven continuous SDVFs were exponential functions. The equation used to create an exponential value function differs for monotonically increasing versus monotonically decreasing preferences. When an evaluation measure is monotonically increasing, it means that higher measure scores always correspond to higher value scores, where the highest measure score has a value of one. Monotonically decreasing exponential functions are used when lower scores of the evaluation measure always correspond with higher value scores. Monotonically increasing and monotonically decreasing value function examples are shown here.

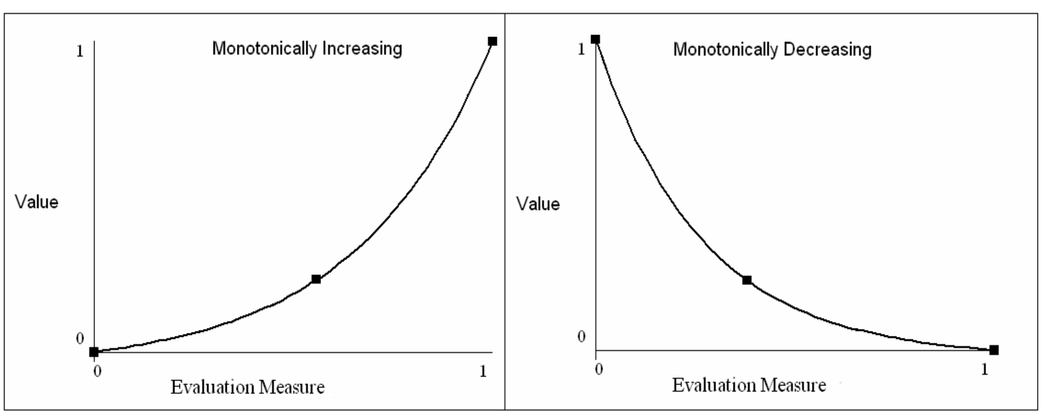

Figure 24: Examples of Monotonically Increasing and Monotonically Decreasing Exponential Value Functions

The equations used to create exponential value functions appear below (Kirkwood, 1997: 236). Equation 2 is for monotonically increasing value functions and Equation 3 is for monotonically decreasing value functions. The equations show that exponential value functions are dependent upon the specified range of measure scores and a constant, ρ. ρ is known as the exponential constant. It determines the shape of the SDVF (Kirkwood, 1997: 236).

$$v_i(x_i) = \begin{cases} \dfrac{1-\exp[-(x_i - x_i^L)/\rho_i]}{1-\exp[-(x_i^H - x_i^L)/\rho_i]}, \rho_i \neq \infty \\ \dfrac{x_i - x_i^L}{x_i^H - x_i^L}, otherwise \end{cases} \tag{2}$$

$$v_i(x_i) = \begin{cases} \dfrac{1-\exp[-(x_i^H - x_i)/\rho_i]}{1-\exp[-(x_i^H - x_i^L)/\rho_i]}, \rho_i \neq \infty \\ \dfrac{x_i^H - x_i}{x_i^H - x_i^L}, otherwise \end{cases} \tag{3}$$

Where:

$v_i(x_i) =$ the exponential single dimensional value function for alternative x on measure *i*

$x_i =$ score for alternative x on measure *i*

$x_i^H =$ the upper bound for alternative x on measure *i*

$x_i^L =$ the lower bound for alternative x on measure *i*

$\rho_i =$ exponential constant for measure *i*

The SDVFs in this research were created with direct input from the decision making team. The first step was to decide whether each measure was continuous or discrete. For discrete evaluation measures, categorical scales were created and defined. To simplify the process of creating exponential SDVFs, a computer software program was used. This program is called Logical Decisions® for Windows. To facilitate the construction of exponential SVDFs in Logical Decisions®, the decision team specified an upper bound and lower bound for each evaluation measure. The team also gave a reference measure score that fell between the upper and lower bounds and earned 50% of the possible value. These three points were then entered into Logical Decisions®, which completed the process of creating the exponential SDVFs. A description of each of the thirteen SDVFs follows.

3.5.1. Construction Branch Single Dimensional Value Functions

The *disturbs natural site features* value uses a binary categorical measure. Management practices that disturb the natural site features near the new building at AFIT are given a value of zero while practices that do not disturb the natural features are given a value of one.

Figure 25: Disturbs Natural Site Features Evaluation Measure SDVF

The evaluation measure for the foot print of each management practice is an exponential value function. Footprint ranged from 0 to 100%. 100% means that the management practice takes up the same amount of space as the area that it receives runoff from. The reference point that receives half of the possible value (0.5) is 25%.

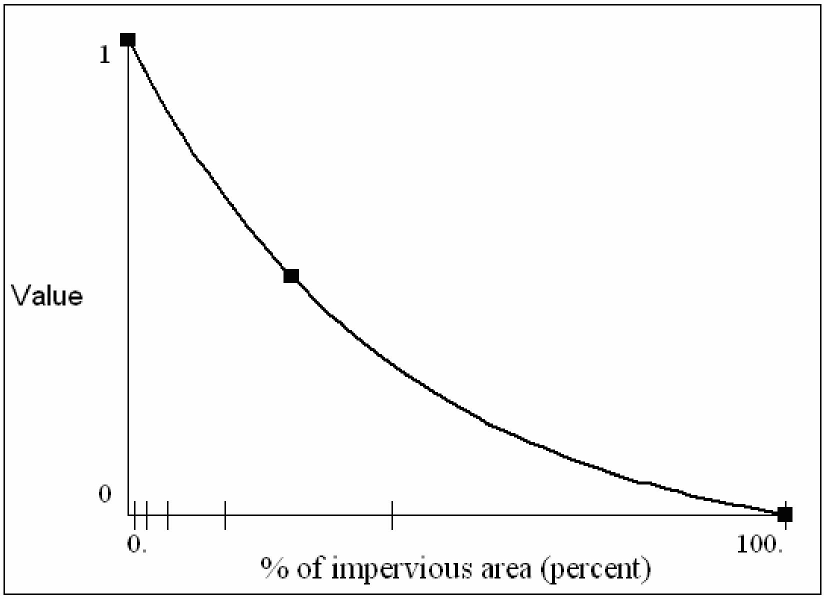

Figure 26: Footprint SDVF

The SDVF for the Installation Burden value is discrete. A management practice alternative with a High burden receives a value score of 0, Medium burden receives a value of 0.333, Low burden receives a value of 0.666, and No burden receives a value of 1.0. An example of a practice with no installation burden is directing runoff into a preexisting ditch to act as a swale, or leaving a grass field in place as open space.

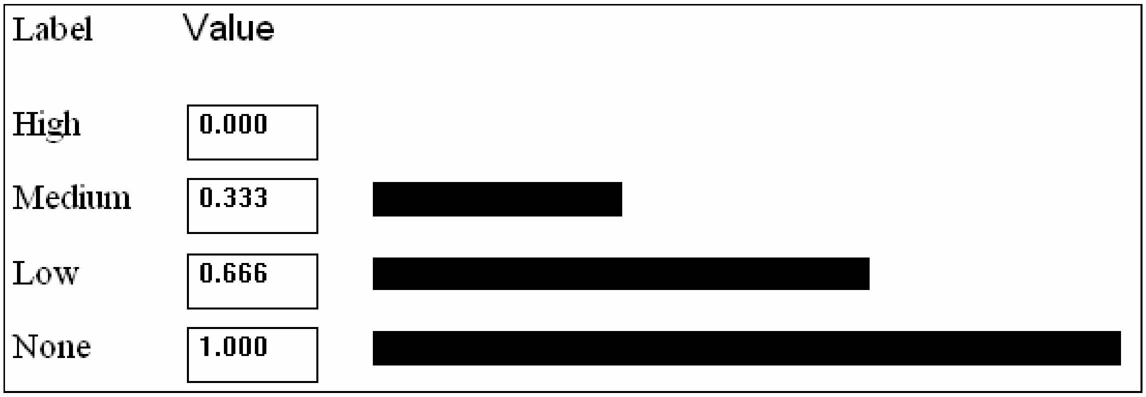

Figure 27: Installation Burden SDVF

Past use in local area also makes use of a discrete SDVF with four categories. These four categories are None, Limited, Moderate, and Extensive. Extensive local use is obviously most preferred while a particular management practice with no local use is least preferred.

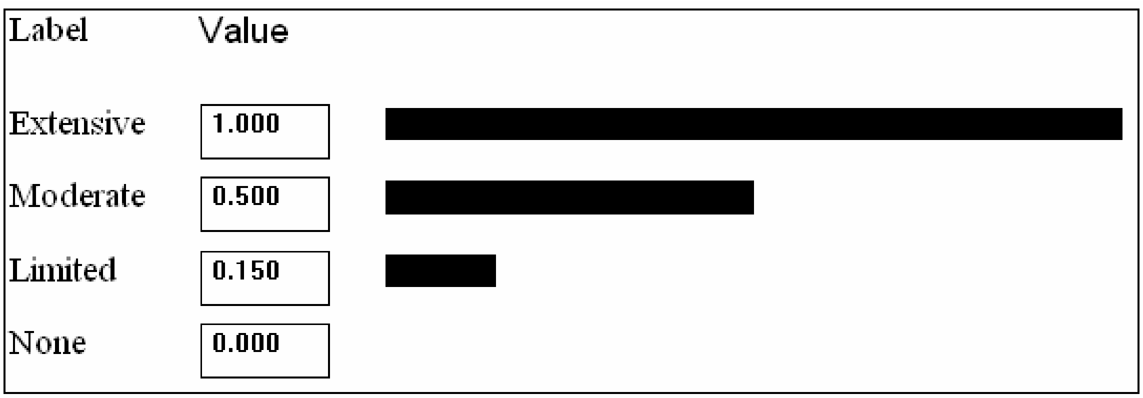

Figure 28: Past Use in Local Area SDVF

The final SDVF in the Construction branch is a binary measure for whether or not an alternative supports the Air Force Sustainable Development Policy Letter.

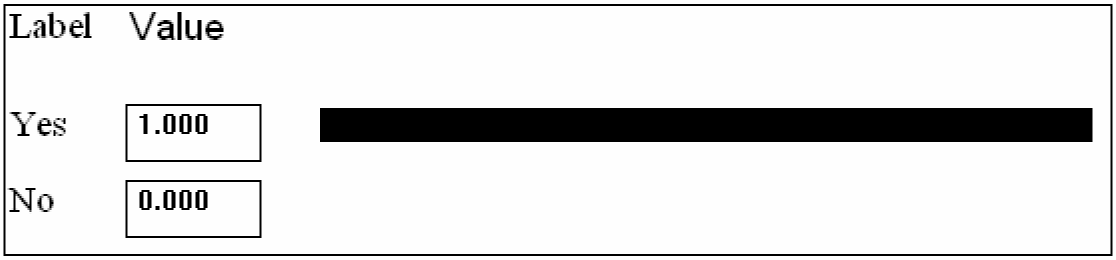

Figure 29: Supports Sustainable Development Policy Letter SDVF

3.5.2. Operations & Maintenance Branch Single Dimensional Value Functions

The Annual Maintenance Cost value is measured in dollars. This is a continuous exponential value function. The range of reasonable annual maintenance costs is from $0 to $4,000. The reference mid-point (i.e. cost that receives 0.5 value score) is $850. This function is monotonically decreasing, which means that lower costs are more preferred.

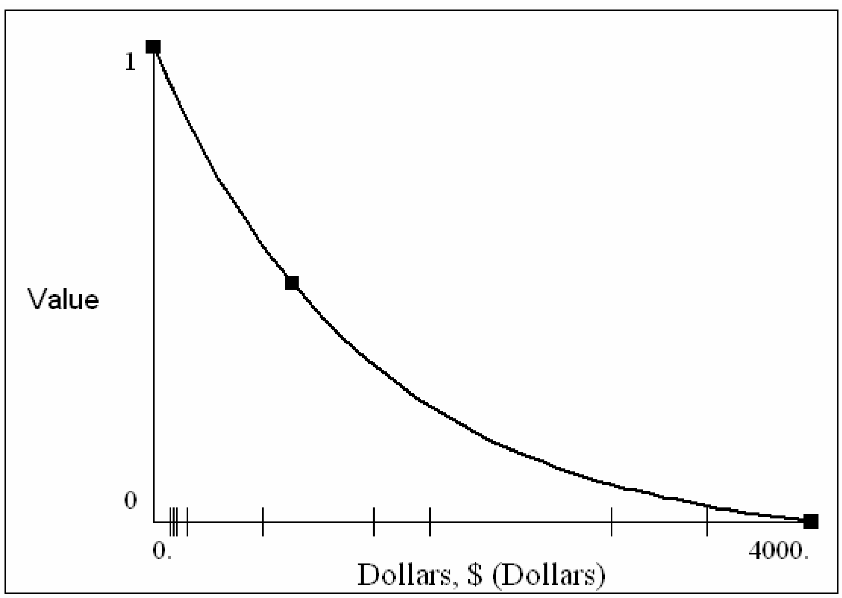

Figure 30: Annual Maintenance Cost SDVF

The SDVF for Simplicity of Maintenance is another discrete function. It has three categories: Easy, Moderate, and Difficult. Easy and Difficult receive value scores of 1 and 0 respectively, while Moderate is a value of 0.5.

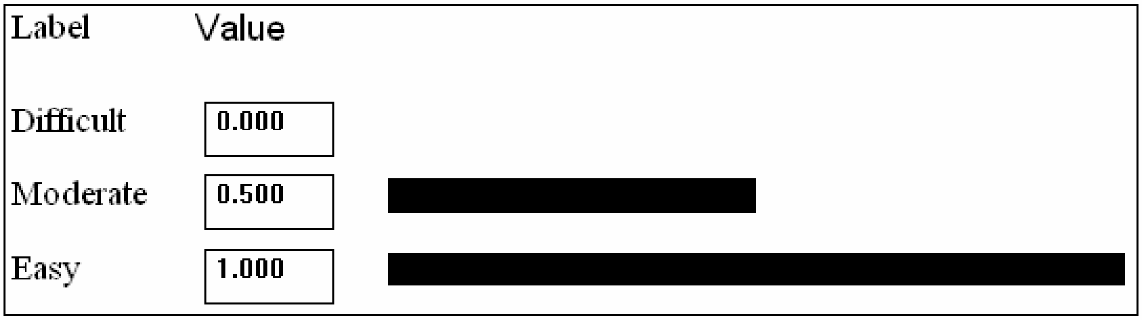

Figure 31: Simplicity of Maintenance SDVF

3.5.3. Performance Branch Single Dimensional Value Functions

The final discrete SDVF in the value hierarchy is for whether or not the management practice can utilize Native Vegetation. This is a binary value function with "Yes" earning a value of 1 and "No" earning a value of 0. The SDVF looks the same as the Supports Sustainable Development Policy Letter SDVF (Figure 29).

The Metals Removal, Nutrient Removal, POL Removal, and TSS Removal SDVFs are all continuous exponential value functions with the same shape. The range of possible alternative scores is from 0 to 100% removal of the pollutant of interest, with a reference mid-point of 75%. Only the Metals Removal SDVF is shown here.

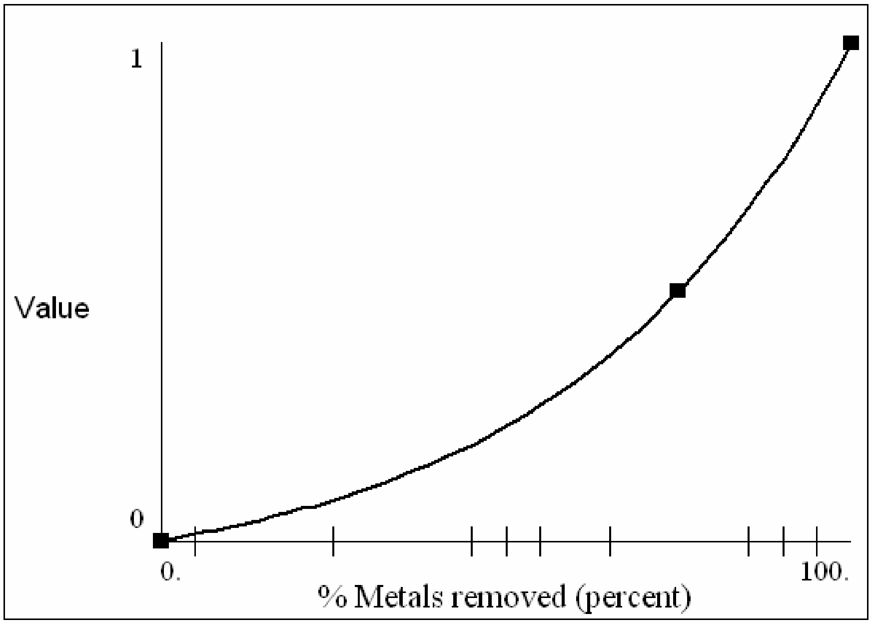

Figure 32: Metals Removal SDVF

The final SDVF in the hierarchy is for the Volume Reduction value. This SDVF is a linear function with a range from 0 to 100%.

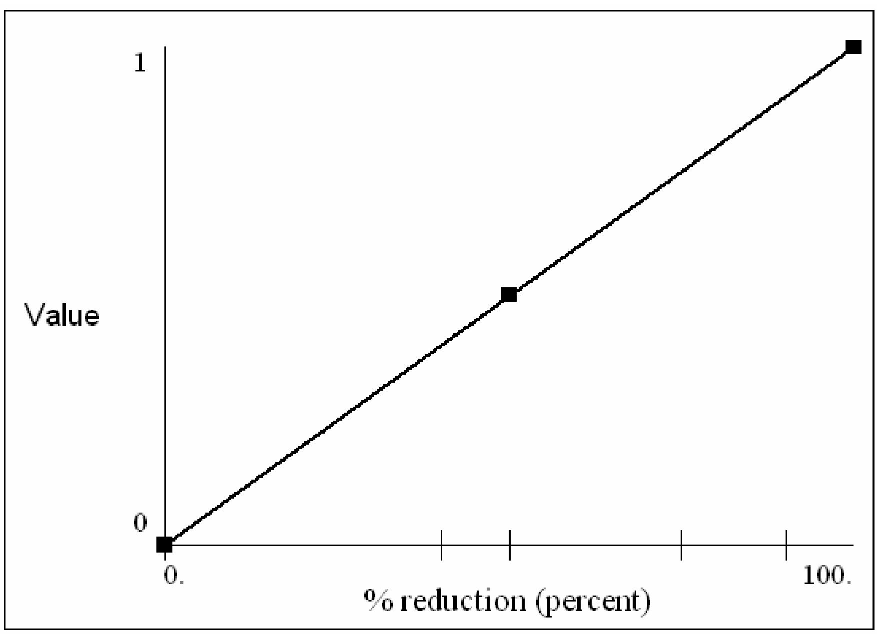

Figure 33: Volume Reduction SDVF

3.6. Step Five: Weight Value Hierarchy

Weighting the value hierarchy takes into account the varying levels of importance that the decision maker places on each value. Values that are more important to the overall decision will be weighted higher than those with less importance. The hierarchy in this research was weighted using the local weighting method described in Chapter 2. Two different techniques were utilized to solicit weights from the decision maker. The first method was direct assessment. For *Annual Maintenance Cost* and *Simplicity of Maintenance*, as well as for *Metals Removal*, *Nutrient Removal*, *POL Removal*, and *TSS Removal*, the decision maker could easily assign weights to those two sets of values. For the other groups of values, a technique called swing weighting was used. The swing weighting process is taken from Kirkwood (1997: 70). The first step in this technique is to rank the values of interest from least preferred to most preferred. The least preferred value is labeled x, while the other values are quantitatively scaled as a multiple of the smallest value. Using the assigned relationships, the weights are rescaled so that they sum to 1. For example, the weights of *Construction*, *Operations and Maintenance*, and *Performance* must sum to one. The order of importance for these three objectives is: *Operations and Maintenance, Construction*, and *Performance*. *Construction* is 1.5 times as important as *Operations and Maintenance*, and *Performance* is 2 times as important as *Operations and Maintenance*. The associated equation is $x + 1.5x + 2x = 1$. Solving for x gives the following weights: *Operations and Maintenance*, 0.2222, *Construction*, 0.3333, and *Performance*, 0.4445. This technique was utilized to find all remaining local weights. The global weight for each evaluation measure was found by multiplying together the local weights for each value directly above it. The global weights are shown in Table 4.

Table 4: Local Weights for Each Value and Global Weights for Evaluation Measures

Local Weights				Global Weight
1st Tier Value	2nd Tier Value	3rd Tier Value	Local Weight	Evaluation Measure
Construction			0.3333	
	Disturbs natural site features		0.1852	0.0617
	Footprint		0.2222	0.0741
	Installation Burden		0.2963	0.0988
	Past use in local area		0.2222	0.0741
	Supports SDPL		0.0741	0.0247
Operations and Maintenance			0.2222	
	Annual Maintenance Cost		0.70	0.1556
	Simplicity of maintenance		0.30	0.0667
Performance			0.4445	
	Native vegetation		0.1667	0.0741
	Treatment Effectiveness		0.3333	
		Metals Removal	0.25	0.037
		Nutrient Removal	0.25	0.037
		POL Removal	0.25	0.037
		TSS Removal	0.25	0.037
	Volume Reduction		0.50	0.2222

Two weights to make note of are those for *Annual Maintenance Cost* at 15.56% and *Volume Reduction* at 22.22%. Because of these weights, we expect these values to significantly impact the overall value scores. *Volume Reduction* is weighted so high because it is a very good measure of the overall pollution prevention capabilities for the alternatives. The decision maker stated earlier that the overall goal of an innovative practice is pollution prevention. Four more weights to look at are those for the four treatment effectiveness values. At the AFIT location on Wright-Patterson AFB, there is no known stormwater contaminant problem; therefore, all four removal effectiveness values are weighted equally. Their total weight adds up to 14.8%. For a decision maker that is aware of a known contaminant problem, he can reassign the weights for these four values, so that the removal value that will take care of his pollution problem will be weighted significantly higher than the others.

3.7. Step Six: Alternative Generation

Chapter 2 discussed the nine alternatives that are compared in this analysis. These nine alternatives were generated after the first five steps of the VFT process were completed. Three alternatives were selected from existing technologies that are already in use today (oil-water separator, wet detention, and infiltration basin). Three more alternatives were developed by selecting technologies that would earn maximum value for a specific evaluation measure. For instance, the sand filter can be installed underground; therefore, it takes up no space above ground, earning a maximum score for the footprint evaluation measure. Similarly, open space design would earn a maximum score for installation burden because you can simply leave part of the site undeveloped. The third alternative developed with this methodology is the infiltration basin because it earns an extremely high score for volume reduction. The vegetated filter strip alternative was developed by trying to minimize the score on the footprint evaluation measure. This methodology was used because alternatives that score very low in one area are typically eliminated; however, it is important to include them in the analysis because they may earn a very high score for other values, making them very competitive overall. Finally, the rain garden and infiltration trench alternatives were generated by reading about their use in pertinent stormwater management literature. Due to existing environmental and building regulations on Air Force installations, conventional stormwater management systems, consisting of storm drains and storm sewers, must be implemented to handle stormwater runoff. Because of this, all alternatives selected are management practices that can be used to reduce the volume or improve the quality of stormwater before it enters the storm sewers.

4. Analysis

4.1. Overview

The analysis section of this research will focus on steps seven, eight, and nine of the ten-step VFT process. In step seven, all alternatives are scored, based on the specified evaluation measures and single dimensional value functions. Step eight consists of performing a deterministic analysis of the total weighted value scores for each alternative. In step nine, the effect of changing value weights is examined through sensitivity analysis. This analysis is completed based on data for Wright-Patterson Air Force Base. In addition to the standard VFT analysis of alternatives, a benefit/cost analysis is performed to determine which alternative has the highest value per dollar ratio. The value scores come from the VFT model while the cost is an estimate of capital cost for constructing each stormwater management practice at Wright-Patterson AFB.

4.2. Step Seven: Alternative Scoring

Collecting data to score each of the nine alternatives is a very important part of the VFT process. Without proper data for each alternative across all evaluation measures, it would be impossible to develop and compare overall value scores to determine the best alternative. Data was collected from a variety of sources for this research. Six main sources were used for a significant amount of the data collection. These include *Municipal Stormwater Management* (Debo and Reese, 2003), *Preliminary Data Summary of Urban Storm Water Best Management Practices* (EPA, 1999a), *Storm Water Technology Fact Sheet* (EPA, 1999c-j), *Low Impact Development* (UFC, 2004), *National Menu of Best Management Practices for Stormwater Phase II* (EPA, 2006a), and *Alternative Stormwater Best Management Practices Guidelines* (PWUD, 2006). Capital cost estimates were required for the benefit to cost analysis. Also, annual maintenance costs were computed as a percentage of capital cost. The literature provided a construction cost for each alternative based off of a cost per cubic foot of treated water volume. For instance, the capital cost of an infiltration trench is estimated at $4 per cubic foot of stormwater (EPA, 1999a). The volume of stormwater entering the treatment practices was needed in order to convert this cost per cubic foot into a single capital cost. This volume was calculated using the size of the impervious area generated by the new AFIT building and its immediate surroundings (in square feet) and the depth of the average rainfall event. The size of the impervious area (67,500 square feet or 1.55 acres) was measured from the Army Corp of Engineers site layout design drawings. Following guidelines provided in the American Society of Civil Engineers Manual, the Ohio EPA calculated that using 0.5 inches as the rainfall depth includes 85% of the average annual storm events. They multiply this number by 1.5 to get 0.75 inches as a conservative estimate for the depth of 85% of the average annual storm events (Ohio EPA, 2006). Based on this data, construction costs of stormwater management practices were based on a design that treats 4,218.75 cubic feet of stormwater at one time. The tables below show scores for each alternative across all bottom tier values. Table 7 also includes approximate capital costs.

Table 5: Alternative Scoring for Construction Branch

	LOWEST LEVEL VALUE				
ALTERNATIVES	Disturbs site features	Footprint	Installation Burden	Past Use	Supports SDPL
Wet Detention	No	3%	Medium	Extensive	Yes
Oil-Water Separator	Yes	1%	High	Extensive	No
Infiltration Basin	No	3%	Medium	Limited	Yes
Infiltration Trench	Yes	3%	High	Limited	Yes
Rain Garden	No	6%	Medium	None	Yes
Open Space	No	40%	Low	Moderate	Yes
Constructed Filter	Yes	1%	High	Limited	No
Grassed Swale	No	15%	Low	Moderate	Yes
Filter Strip	No	100%	Low	Moderate	Yes

Table 6: Alternative Scoring for Performance Branch

	LOWEST LEVEL VALUE					
ALTERNATIVES	Native Vegetation	Metals Removal	Nutrient Removal	POL Removal	TSS Removal	Volume Reduction
Wet Detention	Yes	55%	55%	20%	70%	50%
Oil-Water Separator	No	5%	5%	80%	40%	0%
Infiltration Basin	Yes	85%	60%	30%	75%	90%
Infiltration Trench	No	90%	60%	30%	90%	90%
Rain Garden	Yes	95%	75%	60%	90%	75%
Open Space	Yes	25%	50%	10%	30%	40%
Constructed Filter	No	45%	40%	70%	70%	0%
Grassed Swale	Yes	65%	35%	62%	81%	40%
Filter Strip	Yes	50%	30%	20%	80%	40%

Table 7: Alternative Scoring for Operations and Maintenance Branch and Capital Cost

	LOWEST LEVEL VALUE		
ALTERNATIVES	Maintenance Cost	Simplicity of maintenance	Capital Cost
Wet Detention	$210.94	Moderate	$4,218.75
Oil-Water Separator	$3,360.00	Difficult	$24,000.00
Infiltration Basin	$675.00	Moderate	$8,437.50
Infiltration Trench	$1,687.50	Difficult	$16,875.00
Rain Garden	$1,341.56	Moderate	$22,359.38
Open Space	$112.50	Easy	$2,109.38
Constructed Filter	$2,784.38	Difficult	$25,312.50
Grassed Swale	$126.56	Easy	$2,109.38
Filter Strip	$147.66	Easy	$2,953.13

4.3. Step Eight: Deterministic Analysis

The first step in the analysis is to convert all scores in the three tables above into values. This is done by using the single dimensional value functions created in Chapter 3. The SDVFs convert all scores to a unitless scale, ranging from 0 to 1. The next step is to determine an overall value score for each alternative. This step uses the additive value function that was presented as Equation 1 in Chapter 2. Logical Decisions® uses the additive value function to produce an overall value score for each alternative from the inputted weights and measure scores. "An alternative that has the least preferred score on all of the evaluation measures will have an overall value of zero", while "an alternative that has the most preferred score on all of the evaluation measures will have an overall value of 1" (Kirkwood, 1997: 74). The overall value score tells the decision maker how much of the available value a particular alternative earns. These overall value scores are used to rank the available alternatives; however, they do not denote exactly how much better a higher alternative is than a lower alternative (Kirkwood, 1997). Figure 34 shows the overall value for each of the nine alternatives.

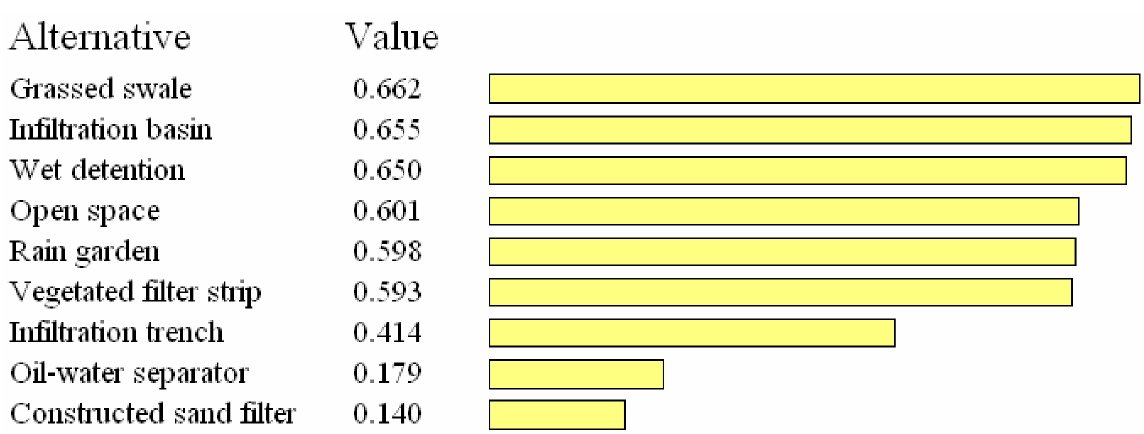

Figure 34: Overall Alternative Rankings

In order to more fully analyze the value ranking shown above, Figure 35 shows how the first tier values in the hierarchy contribute to the overall value for each alternative. While all alternatives score well for the *Construction* branch, the *Performance* and *Operations and Maintenance* branches significantly affect the overall rankings. The top alternative, grassed swale, performed relatively evenly across all three branches in the hierarchy. The second ranked alternative, infiltration basin, scored considerably higher than a grassed swale for the *Performance* value; however, it was lower for both of the other first tier values. The oil-water separator and constructed sand filter both scored well below all of the other alternatives due to their extremely low value scores in *Performance* and *Operations and Maintenance*.

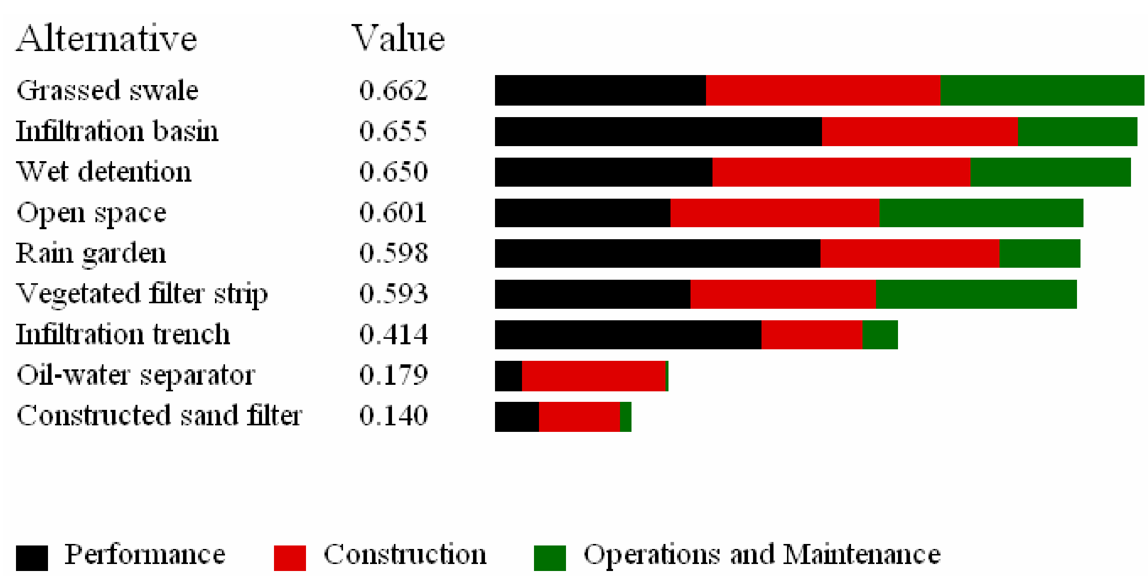

Figure 35: Overall Alternative Rankings Broken Out by First Tier Values

Figure 35 can be broken down even further. All three first tier values can be expanded to show how each bottom tier value contributed to an alternative's overall value score. Figure 36 shows the overall scores broken down into the thirteen lowest level values. In the figure, we see that the black and red bars contribute a significant amount of value to the overall value score. These sections of the bars represent the *Volume Reduction* and *Annual Maintenance Cost* values. As stated in the discussion on weighting the hierarchy, we expected these two values to significantly impact the overall rankings.

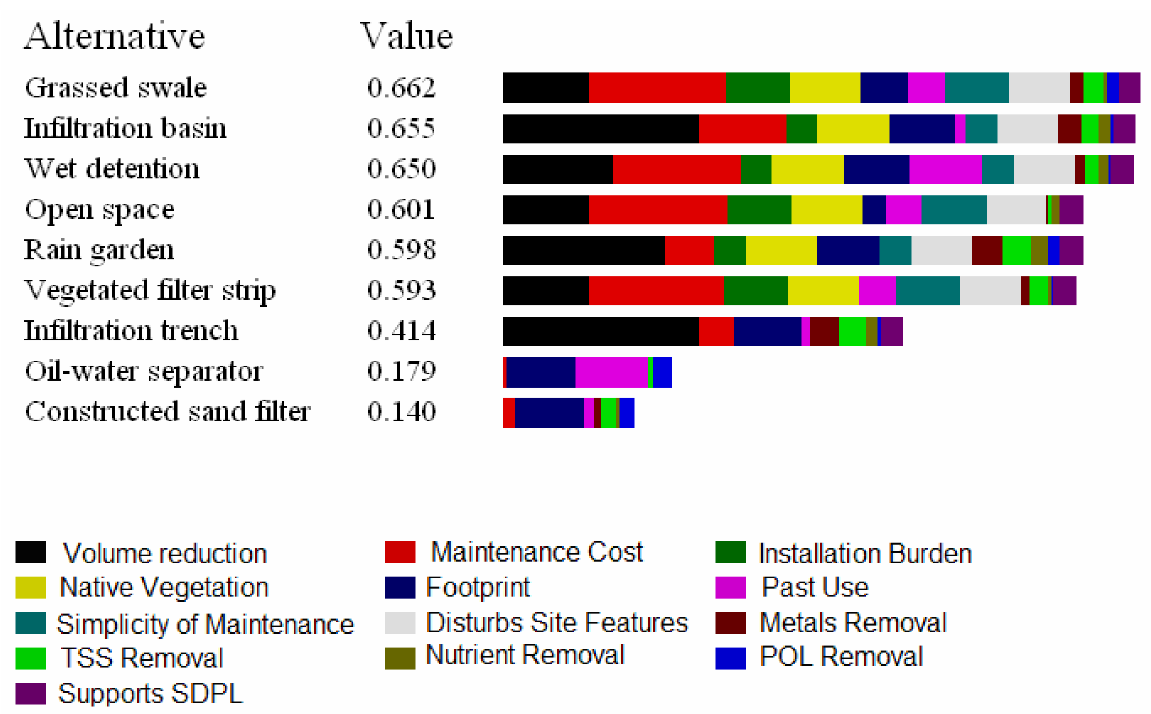

Figure 36: Overall Alternative Rankings Broken Out by Lowest Tier Values

4.4. Step Nine: Sensitivity Analysis

A sensitivity analysis is performed "to determine the impact on the rankings of alternatives of changes in various model assumptions" (Kirkwood, 1997: 82). Changing the weights assigned to certain values enables the decision maker to understand the relative importance that they had placed on the specified value and how the rankings might fluctuate with variations in the weights. If disagreements exist between decision makers about what weights to assign to specific values, sensitivity analysis determines if they have to come to very specific agreements on each weight, or if a range of weights produces the same rankings. In addition, “sensitivity analysis may be useful if the individual building the model is only a proxy for the actual decision-maker” (Jeoun, 2005). Sensitivity analysis is performed by changing the weight of one value while all other weights are adjusted proportionally so that they still sum to one. In this way, the ratio of one value to another remains the same as they were with the original weights. A sensitive value means that the current alternative ranking changes with a reasonable fluctuation in the weight of the specific value. The existence of sensitive values means that the decision maker must either be very confident in the assigned weights, or perform additional research to further refine the allocated weights. The sections below discuss the sensitivity of each value in the hierarchy.

In order to potentially limit the amount of sensitivity analysis performed, sensitivity graphs were first generated for the first tier values: *Construction*, *Operations and Maintenance*, and *Performance*. If the first tier was not sensitive to a change in weight, then further analysis of the lower tier values was unnecessary.

4.4.1. Sensitivity Analysis for *Construction* Value

The original weight for the *Construction* value was 0.333. This is denoted by the vertical line in the figure below. Using Logical Decisions® to adjust the weight of *Construction*, it is found that an increase in the weight to 0.438 makes wet detention the preferred alternative, while a decrease to 0.29 makes an infiltration basin the top ranked alternative. If the decision makers' are confident that the true weight of *Construction* is within 0.29 and 0.438, then a grassed swale remains the top alternative.

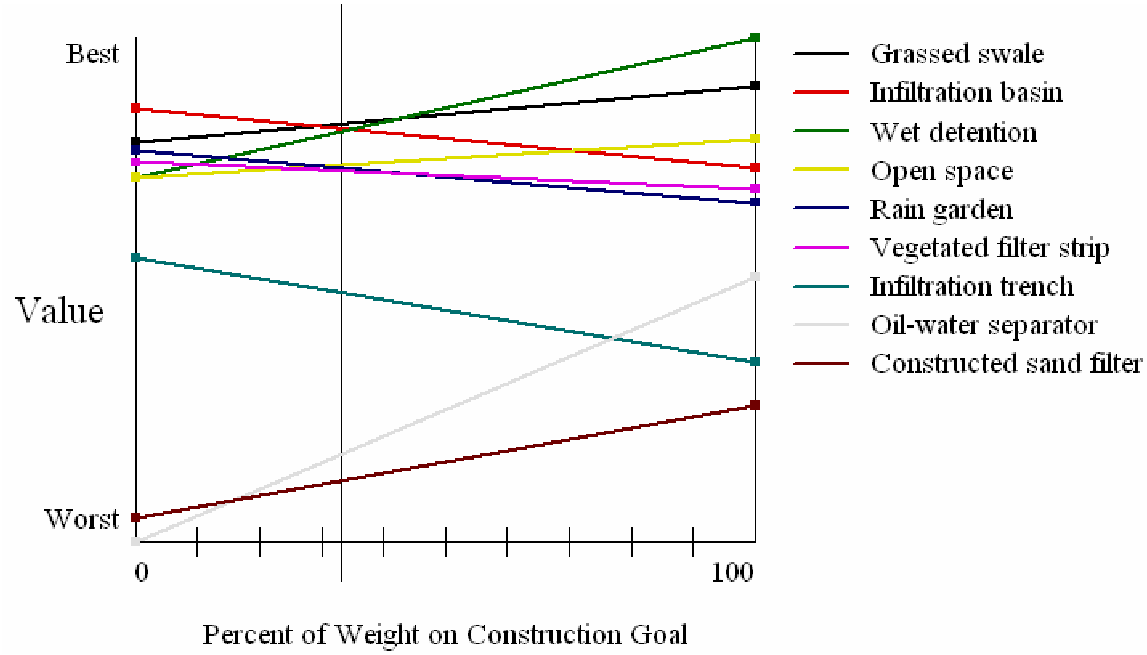

Figure 37: Sensitivity Graph of Construction Value

4.4.2. Sensitivity Analysis for *Operations and Maintenance* Value

The original weight assigned to the *Operations and Maintenance* value was 0.222. Based on the sensitivity graph below, we would expect an increase in the weight to produce no change in the rankings unless the weight rose all the way to 0.925; however, a small decrease in the weight to 0.205 produces a change in the alternative rankings. At all weights below 0.205, an infiltration basin is the preferred alternative. It should also be noted that at 0.222, wet detention is a close third behind the first two alternatives.

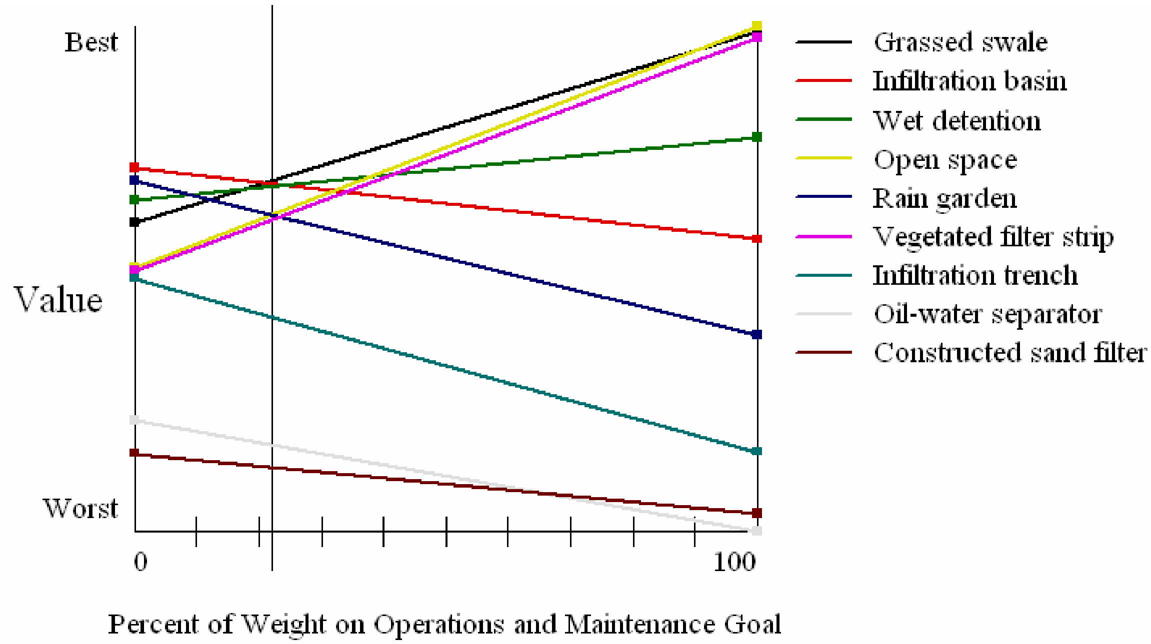

Figure 38: Sensitivity Graph of Operations and Maintenance Value

4.4.3. Sensitivity Analysis for *Performance* Value

The current weight of the *Performance* value is 0.445. As shown in the graph below, a decrease in this weight does not change the first ranked alternative; however, the second alternative changes from an infiltration basin to wet detention. An increase in the weight to 0.46 changes the rankings so that an infiltration basin is first and grassed swale second. At 0.555, a rain garden moves into second rank ahead of a grassed swale. The infiltration basin and rain garden alternatives converge to the same value as the weight of *Performance* approaches 1.0. This is due to a rain garden's higher rate of pollutant removal and volume reduction compared to an infiltration basin.

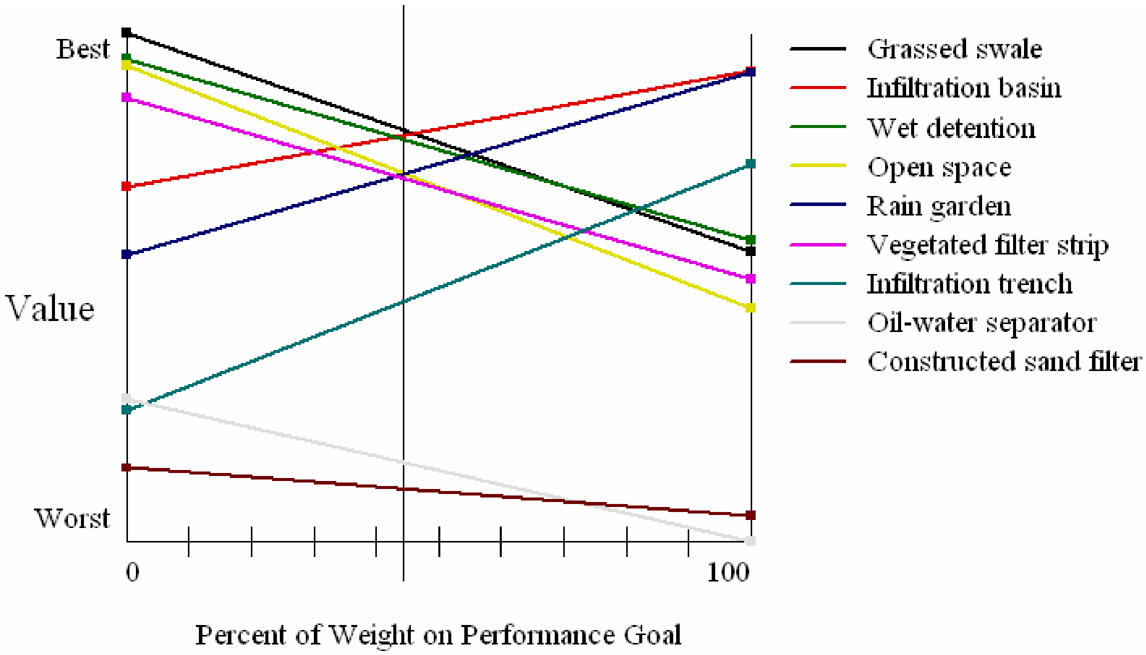

Figure 39: Sensitivity Graph of Performance Value

4.4.4. Sensitivity Analysis for Bottom Tier Values

From discovering that the first tier values are sensitive to fluctuations in the assigned weights, it is necessary to further investigate the sensitivity of the lowest tier values. *Construction*, was the least sensitive first tier value (required 0.105 increase or 0.043 decrease in weight to change rankings), while *Operations and Maintenance* (required 0.017 decrease) and *Performance* (required 0.015 increase) displayed comparable sensitivity.

In the *Construction* branch of the hierarchy, *Disturbs Natural Site Features* and *Supports Sustainable Development Policy Letter* were not sensitive. Because the measures for both of these values are binary, the nine alternatives are clumped into two groups: those receiving a value of 1 and those receiving a value of 0. Although numerous alternatives have extremely close value scores across the range of weights, the grassed swale alternative dominates the rankings for all weights ranging from 0 to 1 for both of these values.

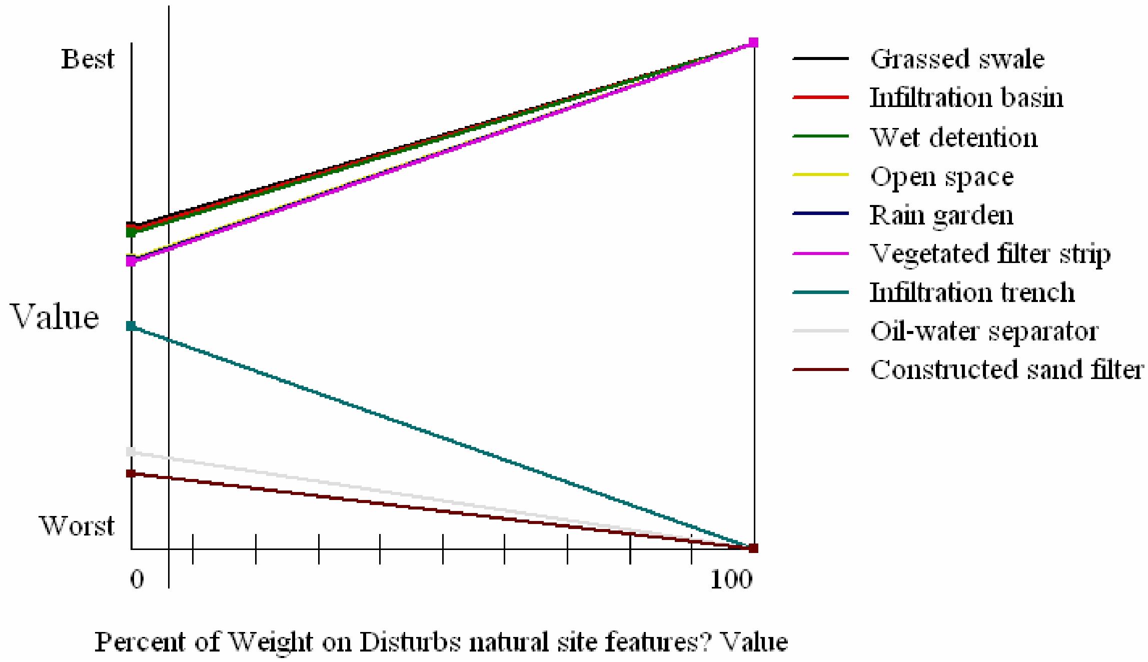

Figure 40: Sensitivity Graph of Disturbs Natural Site Features Value

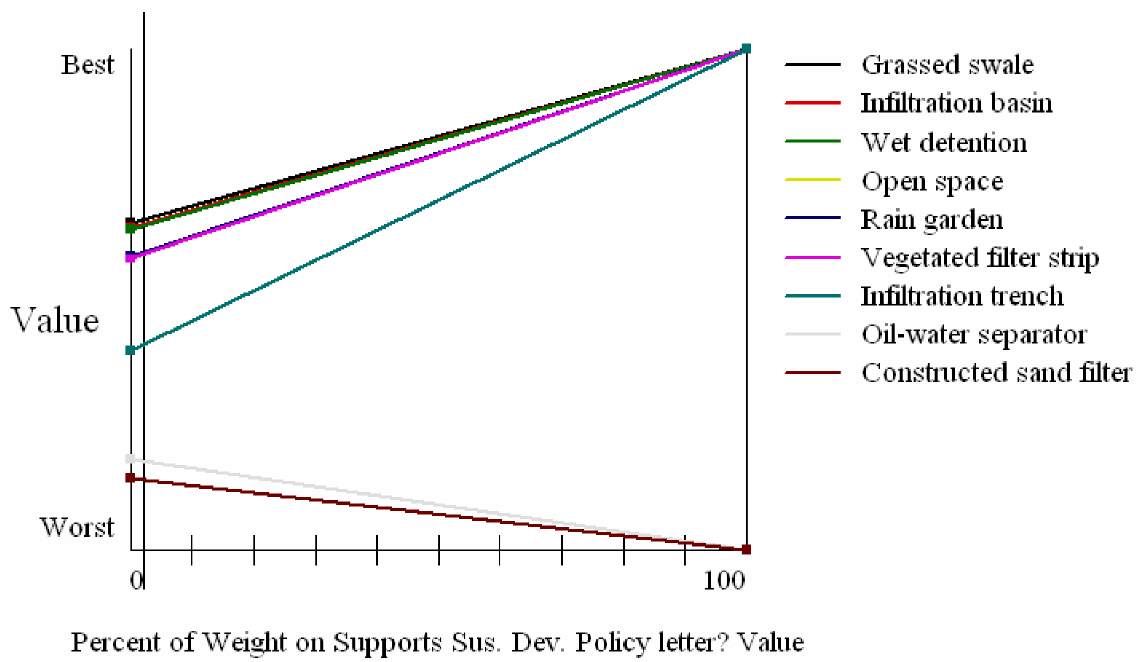

Figure 41: Sensitivity Graph of Supports S.D.P.L. Value

The *Construction* branch values of *Footprint*, *Installation Burden*, and *Past Use in Local Area* are all very sensitive to a change in weight. *Past Use in Local Area* is the most sensitive value. A small increase in the weight will make wet detention the preferred alternative, while a small decrease will make an infiltration basin the preferred alternative. The original weight assigned by the decision maker is 0.074. From 0.098 to 1.0, the wet detention alternative clearly dominates all other options.

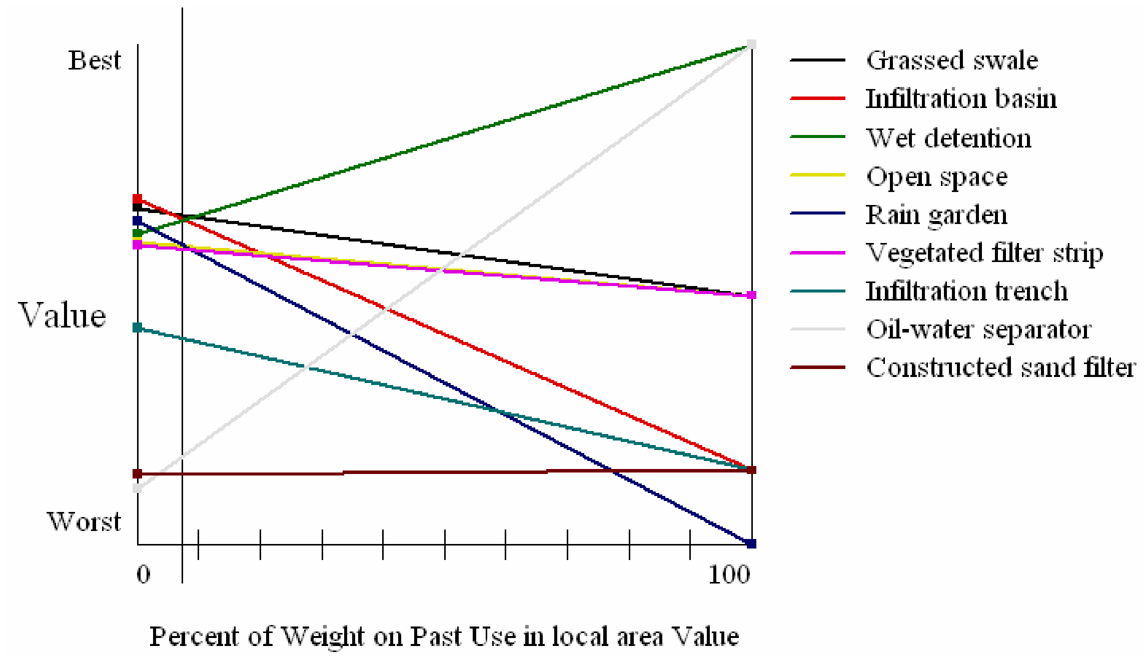

Figure 42: Sensitivity Graph of Past Use in Local Area Value

For the *Footprint* value, a small weight increase from 0.074 to 0.103 makes the infiltration basin and wet detention alternatives become more preferred than the grassed swale alternative. For the *Past Use in Local Area* value, a small weight decrease from 0.074 to 0.055 effects a change in the rankings so that infiltration basin is the top ranked option.

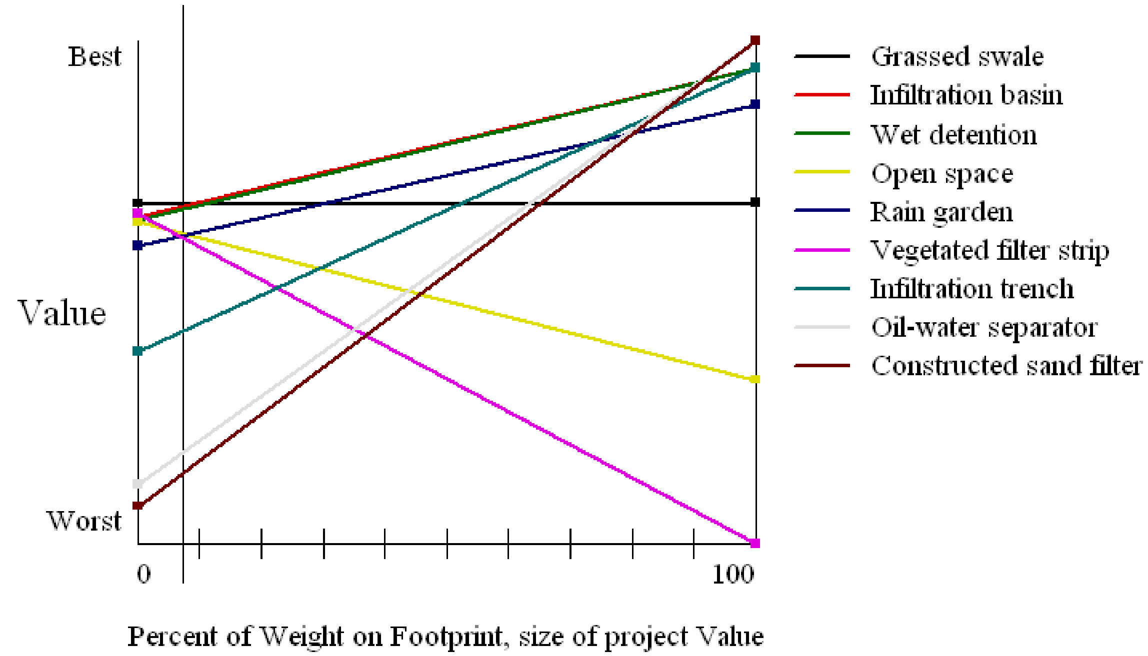

Figure 43: Sensitivity Graph of Footprint Value

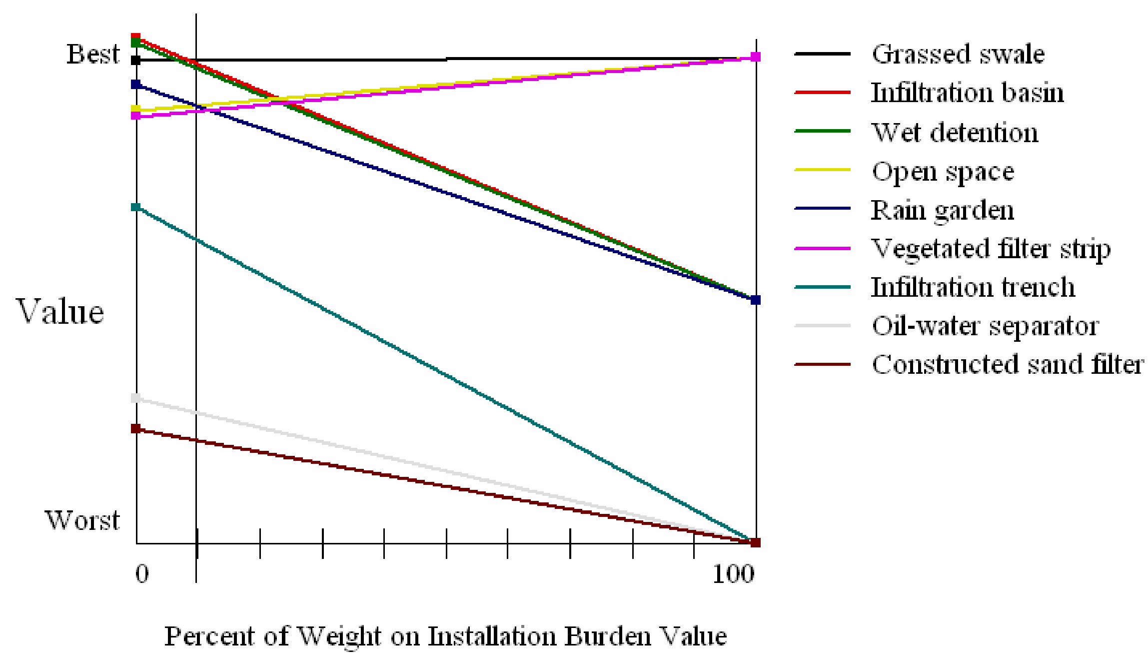

Figure 44: Sensitivity Graph of Installation Burden Value

In the *Operations and Maintenance* branch, both values are sensitive to a decrease in the assigned weight. *Annual Maintenance Cost* requires a weight decrease of 0.021

and *Simplicity of Maintenance* requires a decrease of 0.017 for the preferred alternative to change from grassed swale to infiltration basin. Because these two values are only sensitive to a small decrease in the assigned weight, the decision maker should not be concerned with further refining the weights if he knows there is no way the weights will be lower. If his initial weights represent the minimum importance he would ever place on these two values, then he can be confident that the model ranking is accurately reflecting his values and preferences. If the original weights are not the minimums, then the decision maker should do further research to pinpoint an exact weight for each value.

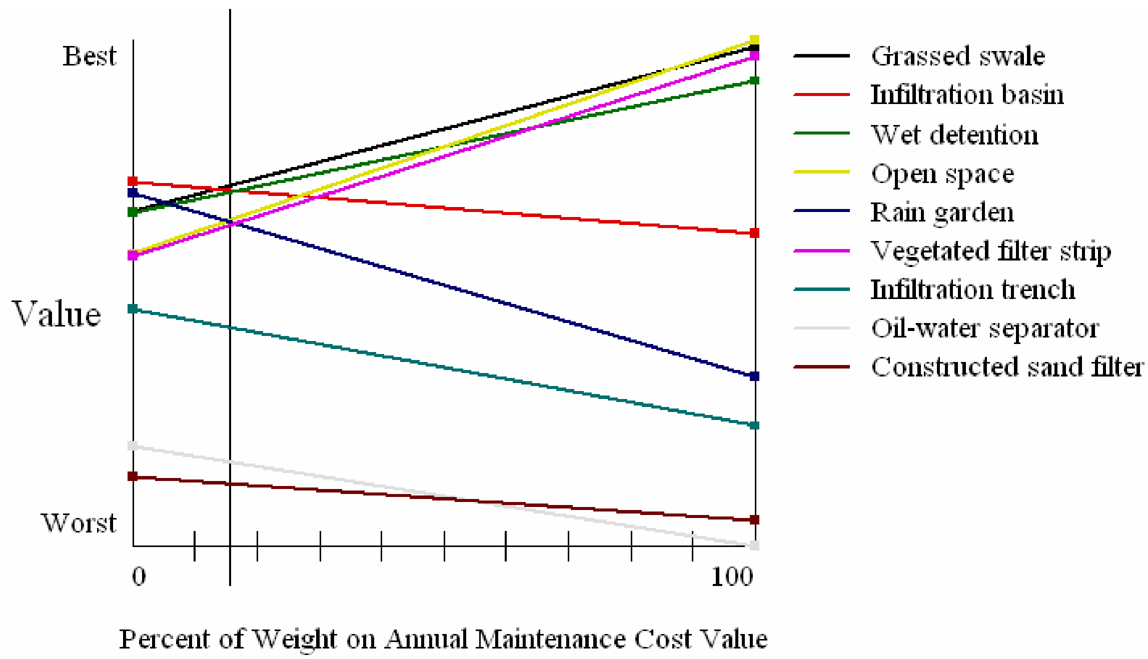

Figure 45: Sensitivity Graph of Annual Maintenance Cost Value

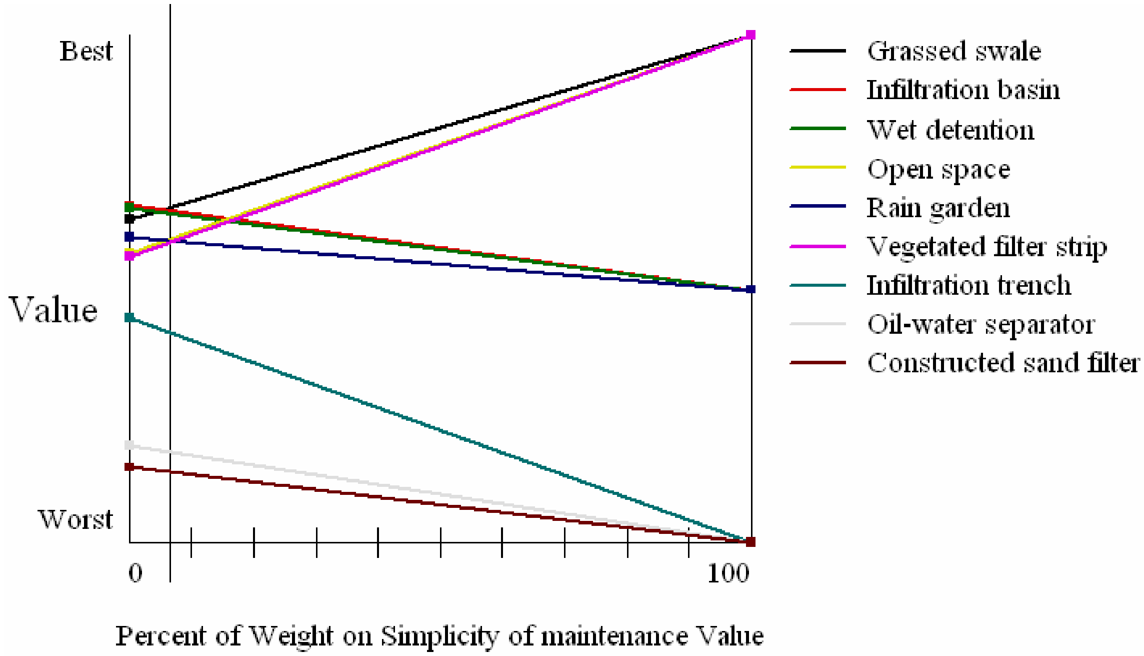

Figure 46: Sensitivity Graph of Simplicity of Maintenance Value

The sensitivity graph for the *Native Vegetation* value looks exactly the same as the graph for *Disturbs Natural Site Features* except the initial weight line slides to the right from 0.062 to 0.074. The grassed swale alternative dominates the ranking for all weights. The sensitivity graph for *Volume Reduction* is very similar to that of the *Performance* first tier value. This is due to the fact that the weight assigned to *Volume Reduction* accounts for 50% of the *Performance* branch's total weight. At the current *Volume Reduction* weight of 0.222, the grassed swale is first, while a slight increase to 0.235 makes an infiltration basin the preferred alternative.

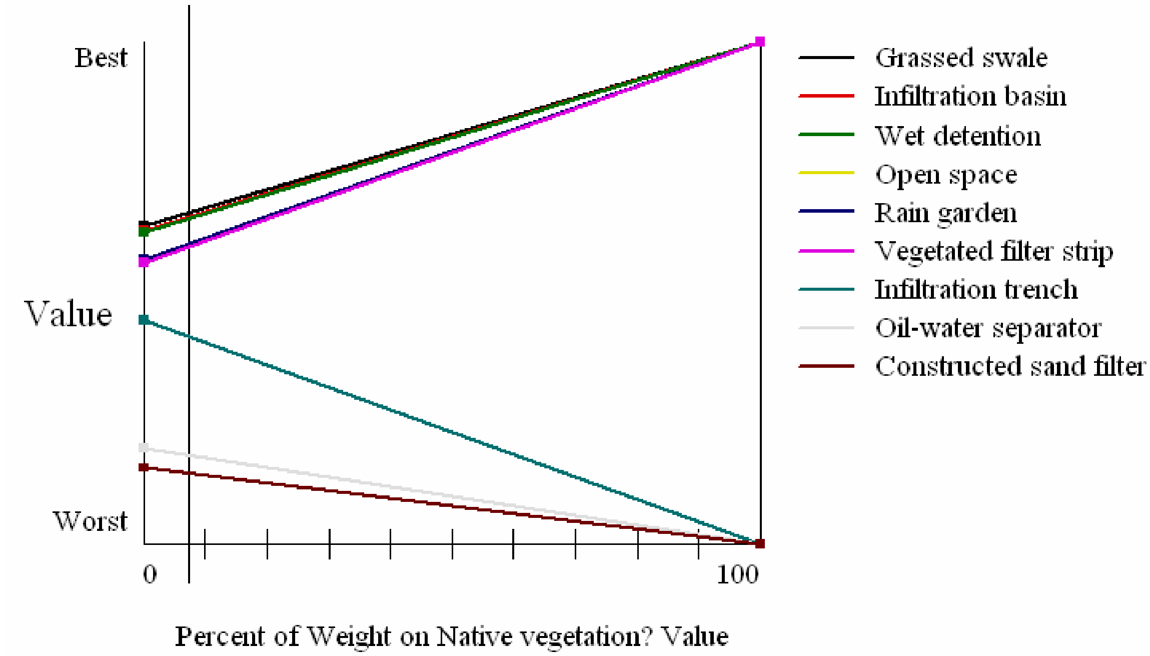

Figure 47: Sensitivity Graph of Native Vegetation Value

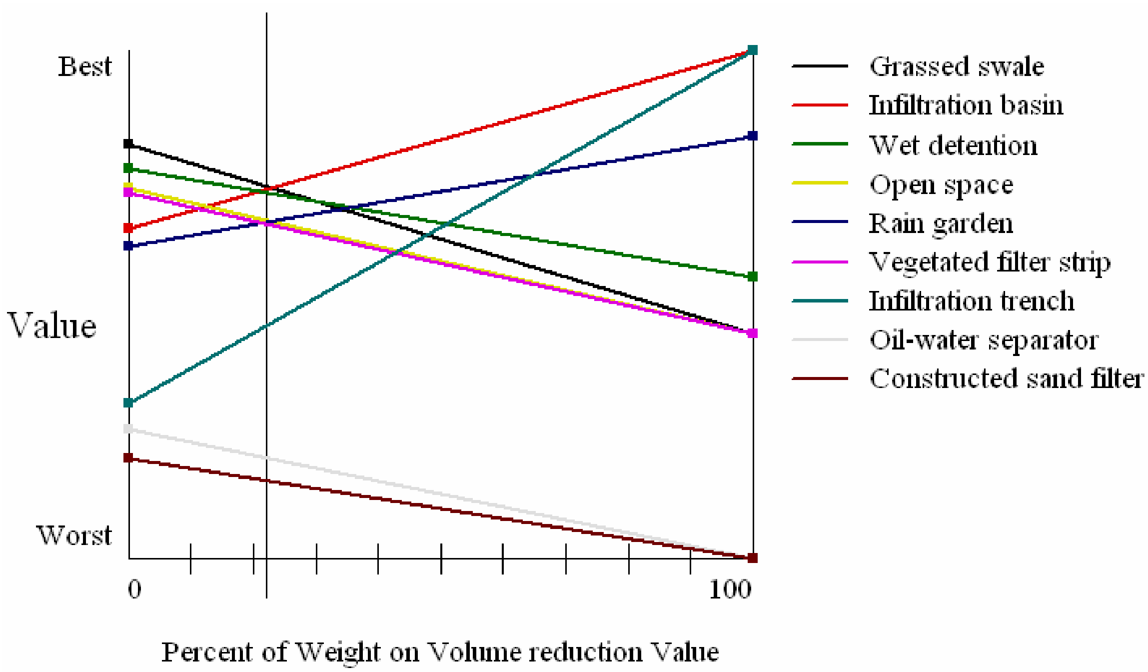

Figure 48: Sensitivity Graph of Volume Reduction Value

The four remaining *Performance* branch values, *Metals Removal*, *Nutrient Removal*, *POL Removal*, and *TSS Removal*, are all not sensitive to a decrease in the original decision maker assigned weights. *POL Removal* is also not sensitive to a reasonable increase in the weight; however, Figure 49, shows that for extremely high *POL Removal* weights, the oil-water separator and constructed sand filter become the top two options. This is the only sensitivity graph that shows either of these two alternatives as the preferred option for even a small portion of the weight range. This graph makes it evident that an oil-water separator and constructed sand filter are only reasonable alternatives when a serious POL contaminant problem exists at a specific location.

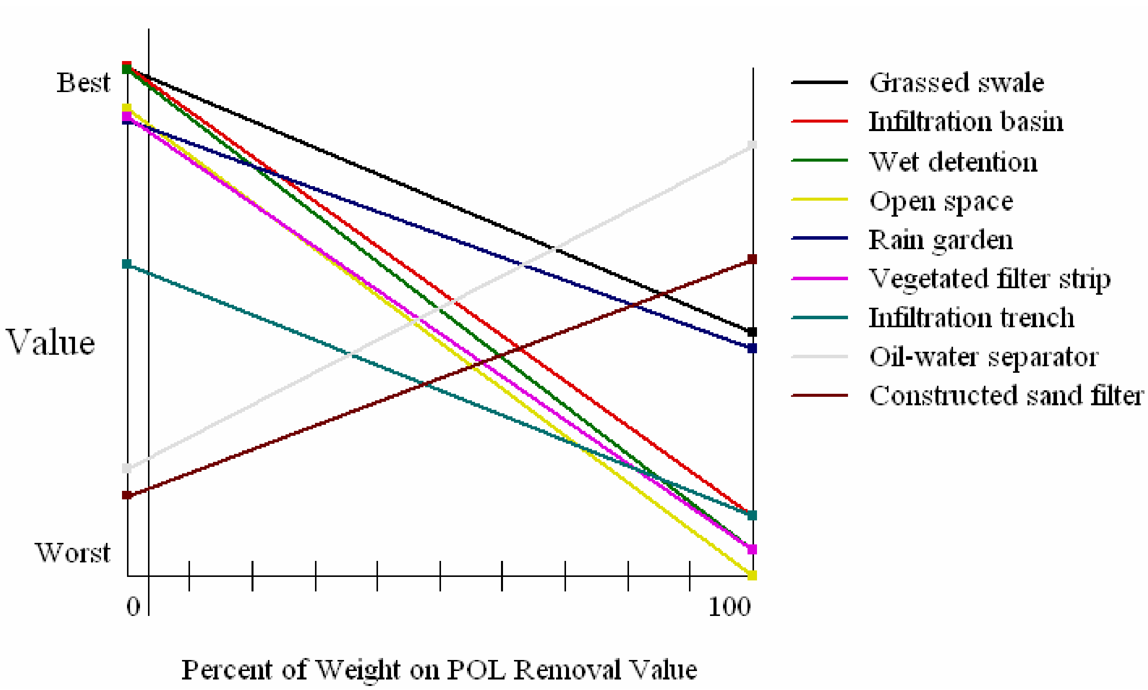

Figure 49: Sensitivity Graph of POL Removal Value

The *TSS Removal* value requires a fairly large increase in weight for a change in the alternative ranking. With an increase in weight of 0.261, the rain garden alternative becomes the preferred option. As with the oil-water separator for a POL contaminant problem, a rain garden would only top the rankings when a serious TSS contaminant situation exists. In this instance, the decision maker using this VFT model would need to ensure that the weight assigned to *TSS Removal* is adjusted enough to capture his specific preference.

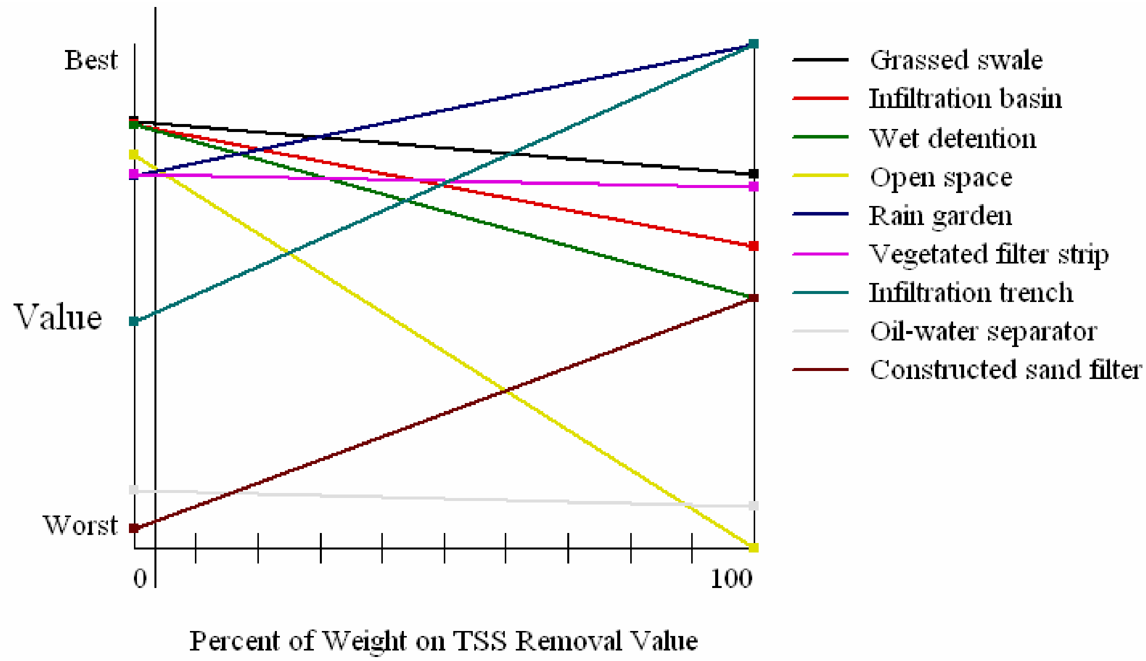

Figure 50: Sensitivity Graph of TSS Removal Value

For both the *Metals Removal* and *Nutrient Removal* values, a modest increase in the assigned weights would cause a change in the ranking of alternatives so that an infiltration basin becomes the preferred option. The rain garden becomes the top ranked alternative if there is a more significant increase in the weight of either value (up to 0.245 for *Metals Removal* and 0.265 for *Nutrient Removal*). The change in the ranking of alternatives at higher weight levels, shown in the sensitivity graphs for *TSS Removal*, *Metals Removal*, and *Nutrient Removal*, reflect a rain garden's high level of treatment effectiveness for TSS, metal, and nutrient contaminants.

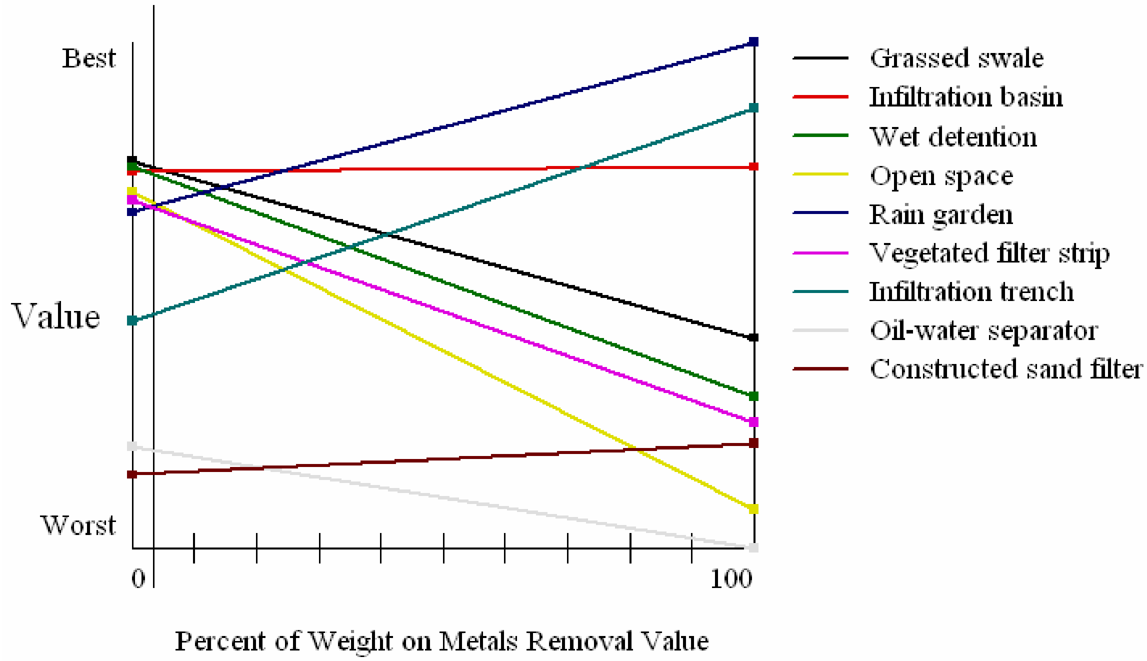

Figure 51: Sensitivity Graph of Metals Removal Value

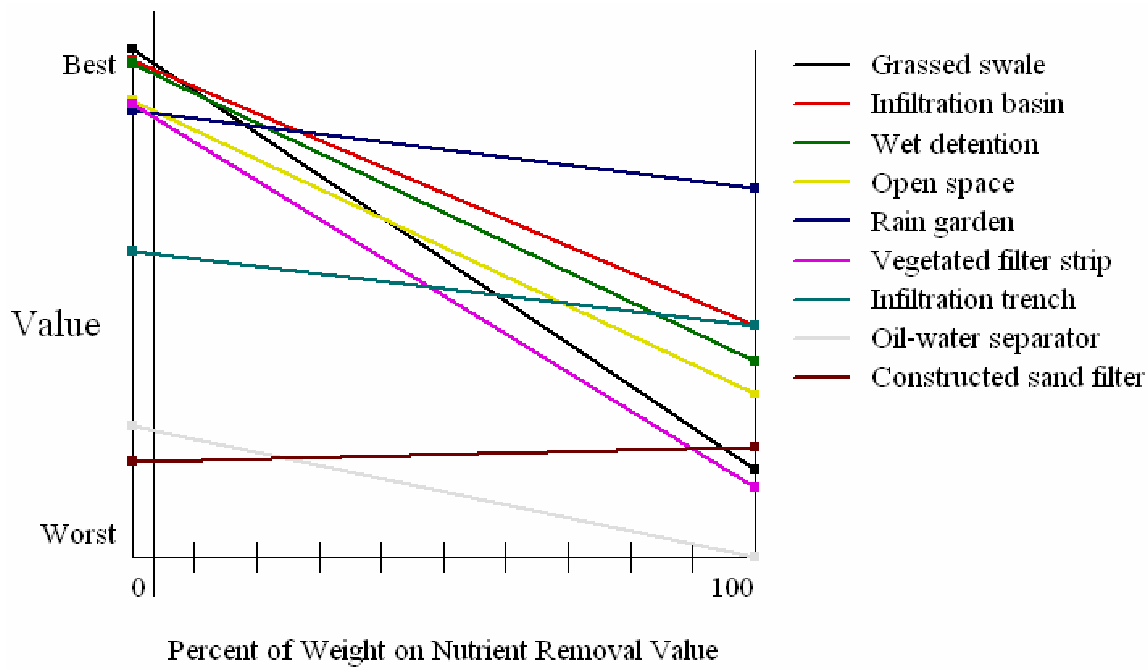

Figure 52: Sensitivity Graph of Nutrient Removal Value

It is possible to make several conclusions from this sensitivity analysis. The first is that at the current assigned weight, the grassed swale is the top ranked alternative. It is also evident that both the wet detention and infiltration basin become viable alternatives for a small increase or decrease in the assigned weight. Finally, other alternatives, such as the rain garden or oil-water separator, may become the preferred alternative if the decision maker assigns a very high weight to a pollutant removal value. It is likely that a decision maker would do this if he was aware of a known contaminant problem at his location, and his whole reason for implementing the innovative stormwater management technology was to correct this problem.

4.5. Benefit/Cost Analysis

The value hierarchy created by the decision making team did not include capital cost. When selecting a stormwater management practice, up front construction cost is obviously one of the major factors in deciding which alternative to implement. If sufficient funds do not exist in the budget for particular alternatives, then there is no way to implement them. For this reason, capital cost should be one of the most important values when making a complex, multi-objective decision; nevertheless, putting capital cost in a hierarchy can easily violate one of the five desirable characteristics of a value hierarchy: independence. Recalling from Chapter 2, independence means that the score assigned to each evaluation measure must not depend on the score of any other evaluation measure. A lack of independent values "causes difficulties when attempting to develop a procedure to combine evaluation measures to determine the overall preferability of alternatives" (Kirkwood, 1997: 18). For instance, for constructing a stormwater management practice, capital cost is most likely not independent of *Installation Burden* and *Footprint*. Projects with a large footprint and high installation burden probably cost more than smaller and simpler alternatives. The value earned from an alternative with a small footprint and low installation burden would most likely be double counted when that alternative received additional value for a low capital cost. In order to solve this dilemma, a benefit/cost analysis is performed.

A benefit/cost analysis attempts to calculate the “bang-for-buck” for each alternative. This means that an analysis is performed to determine which alternative earns the most value per dollar spent. This methodology is not only beneficial for determining how to garner the most value from each dollar, but is also beneficial in allocating resources based on an assigned budget. The first step in the process is to complete the VFT analysis to calculate an overall value score for each alternative. Next, the value score is divided by the cost of the project and multiplied by some factor of ten to produce a number that is easier to work with. For example, a value score of 0.25 divided by a cost of $3000 creates a benefit/cost ratio of 0.0000833. Multiplying this number by 10,000 delivers a ratio of 0.833 which is much easier to compare to other values. The benefit/cost ratio for each alternative must be multiplied by the same factor of ten in order to create a meaningful analysis. Alternatives with a higher benefit/cost ratio are more preferred than alternatives with a lower ratio. All alternatives are then ranked in order from most preferred to least preferred. The decision maker then selects alternatives from the list in order from most preferred to least preferred. As he selects an alternative, the cost is subtracted from the total budget. The decision maker then continues to select alternatives until he has no funds left to allocate. Although the nine stormwater management practices presented in this research are effective as stand alone treatment measures, they work most effectively when paired together in series. Therefore, the benefit/cost resource allocation methodology is especially helpful when selecting multiple stormwater management practices for projects with a set budget.

The capital cost for each of the nine alternatives and the overall value score for each alternative are presented in table 8 below. The table also shows the benefit/cost ratio for each alternative, as well as the preference rankings based on overall value, capital cost, and benefit/cost ratio (a rank of 1 is most preferred while a rank of 9 is least preferred). The grassed swale is the top ranked alternative for all three ranking methodologies. This is due to its relatively low capital cost and its steady performance across all of the decision maker's values. While the infiltration basin is ranked second based only on value, it moves to fifth based on the benefit/cost analysis. Wet detention and the rain garden also are less preferred, moving from third to fourth, and from fifth to sixth, respectively. The open space alternative moves from fourth to second rank and the filter strip moves from sixth to third. The infiltration trench, oil-water separator, and sand filter all maintain their current positions as the three least preferred alternatives. Examining table 8, it is evident that the benefit/cost rank generally mirrors the rank of alternatives based only on capital cost. Although this is not to be expected for all benefit/cost analyses, it does make sense in this specific analysis because of the wide range of capital costs for the various alternatives. A decision maker who is most concerned about how a particular alternative achieves his specified values should choose stormwater management practices based on the overall value rank, while a decision maker who is more concerned about upfront cost should take the benefit/cost rank of alternatives into consideration when making his decision.

Table 8: Benefit/Cost Summary Table

	Overall Value	value rank	Cost	cost rank	Benefit/Cost	B/C rank	Delta*
wet detention	0.650	3	$4,218.75	4	1.54	4	+1
oil-water separator	0.179	8	$24,000.00	8	0.07	8	0
infiltration basin	0.655	2	$8,437.50	5	0.78	5	+3
infiltration trench	0.414	7	$16,875.00	6	0.25	7	0
rain garden	0.598	5	$22,359.38	7	0.27	6	+1
open space	0.601	4	$2,109.38	1	2.85	2	-2
sand filter	0.140	9	$25,312.50	9	0.06	9	0
grassed swale	0.662	1	$2,109.38	1	3.14	1	0
filter strip	0.593	6	$2,953.13	3	2.01	3	-3

*Delta is the difference between the Benefit/Cost rank and the overall value rank. Since the most preferred alternative has a rank of 1, a positive delta means the alternative increased in rank and therefore, is less preferred, while a negative delta denotes a lower rank and more preferred.

5. Conclusions and Recommendations

5.1. Overview

This chapter encompasses step ten of Shoviak's ten-step value-focused thinking process: conclusions and recommendations. Within the following sections, the complete research effort is summarized. The research questions proposed in Chapter 1 are reviewed, the benefits and limitations of the VFT process and associated decision model are discussed, and future research recommendations are presented.

5.2. Research Summary

Five research questions were proposed in Chapter 1 in order to guide this research and to aid in developing a meaningful decision analysis model. Each question, and a summary of findings are presented here.

What environmental and economic concerns are associated with stormwater runoff in developed areas? Stormwater runoff from developed areas has many adverse effects for both human health and the environment. Runoff often contains high levels of metal contaminants, nutrient contaminants, suspended solids, and POL (petroleum, oils, and lubricants) contaminants. Discharge of these pollutants into local bodies of water creates the risk of contaminating drinking water supplies and polluting water sources used for local recreation activities. High volume flow rates and high contaminant loads can also cause flooding, erosion, and both terrestrial and aquatic habitat degradation. Poor stormwater management can create a significant economic burden on communities when they are forced to repair the damage caused by their lack of stormwater planning. Part II of the National Pollutant Discharge Elimination System requires industrial, municipal, and construction sites to comply with stormwater regulations for collection and treatment of runoff. These entities are also responsible for implementing best management practices to lessen the detrimental effects caused by the existence of impervious surfaces.

What innovative stormwater management technologies have been used successfully in the past? Innovative stormwater management technologies have been used with great success throughout many countries around the world. They have been implemented in all climates; however, some modifications are necessary to specific management practices when used in extremely arid or cold locations. Some management practices, such as wet detention basins, grassed swales, and oil-water separators are already widely used on Air Force installations. Rain gardens are becoming an increasingly popular stormwater management alternative. Prince George's County in Maryland, is the country's leading authority of rain garden design and construction. In the vicinity of Wright-Patterson Air Force Base, Sanitation District Number 1 of Northern Kentucky has had notable success in their use of several best management practices, including "a vegetated roof, riparian zone restoration/ preservation, storage practices such as wet and dry detention basins and a cistern, porous pavements, oil/water separators and vegetated infiltration ditches" (SD1, 2006). In past use throughout the United States, many stormwater BMPs have had high rates of failure due to improper maintenance and poor design. With increased research in natural runoff hydrology, design changes can improve BMP performance; nevertheless, proper maintenance is still a prerequisite for a stormwater management technology to achieve a high level of treatment effectiveness.

What features, advantages, and disadvantages exist for specific innovative stormwater management technologies? This research focuses on nine different stormwater best management practices: wet detention, oil-water separator, infiltration basin, infiltration trench, rain garden, open space design, constructed sand filter, grassed swale, and vegetated filter strip. The specific characteristics of each one was presented in Chapter 2. As a group of stormwater management measures, these BMPs have many benefits. Some are exceptionally good at reducing runoff volume, while others are more appropriate for water quality treatment. The advantage of implementing any of the above control measures is that the stormwater generated on a specific site will be reduced in volume, flow rate, and/or contaminant levels. One disadvantage of using these BMPs is that they have a higher maintenance demand compared to a conventional curb, drain, and storm sewer design.

What are Air Force decision makers' values when selecting stormwater management strategies? Air Force decision makers have three main areas of concern when selecting a stormwater management strategy. Construction, operations and maintenance, and performance issues are all important. Decision makers desire a management practice that has a limited impact on the existing natural site features. They also value a control measure that has a low installation burden and has been successfully implemented in other locations. Implementing sustainable development practices is also important. Other factors that contribute to management strategy selection are annual maintenance cost, simplicity of maintenance, volume and contaminant reduction effectiveness, and overall capital cost.

Is Value-Focused Thinking an appropriate decision making methodology for selecting stormwater management technologies for use on Air Force installations? VFT is an appropriate methodology to use to aid Air Force decision makers in evaluating and implementing stormwater management practices. VFT is a quantitative multi-objective approach to decision making. This is appropriate for BMP selection because of the various competing objectives that exist for the decision situation. VFT helps decision makers to clearly identify their values and then to select a stormwater control measure that best meets their specific requirements.

5.3. Value Model Benefits

Building this VFT model helped facilitate the decision makers in thinking through the exact decision situation and articulating the issues that are of value to them. The VFT model is an objective multi-objective mathematical model that helps to minimize the impact of subjective biases that usually occur for complex decisions. The model was used to analyze stormwater management strategy selection for the new AFIT academic building at Wright-Patterson Air Force Base; however, it can be implemented for other buildings on the base and for other installations. Additional alternatives not presented in this research can also easily be incorporated into the model. The only necessary step required to analyze other alternatives is to collect the necessary data required to score that alternative for each evaluation measure. The deterministic analysis enables the decision maker to see the strengths and weaknesses of each alternative, while the sensitivity analysis shows how a change in the assigned value weights can impact the overall alternative ranking.

5.4. Model Limitations

One of the model benefits listed above is that the VFT hierarchy can be used for stormwater selection in other locations. In order for this to be true, the decision maker at the new location must carefully analyze the assigned weights and determine if his specific decision situation warrants an adjustment of any of the weights. The decision model developed in this research is based on several assumptions. It assumes the existence of moderate climate conditions and soils with moderate to high permeability. For extremely arid or cold climates, all BMPs may not function with the same effectiveness as reported in this research. Poorly permeable soils can also cause the management practice to experience slow drainage times causing several problems such as flooding, safety hazards, or mosquito breeding. Because of these specific conditions, design alterations may have to be made for some of the alternatives which would affect the capital cost. The model also does not take into account any regulations or policies that prohibit the installation of alternative stormwater management practices in specific locations.

5.5. Future Research

As stated at the end of Chapter 4, alternative stormwater management technologies work best when used in combination with one another. For example, using a grassed swale as a pretreatment device for a sand filter takes advantage of the contaminant removal and volume reduction properties of both measures. Further research can be conducted in which the treatment alternatives are various combinations of BMPs. In order for this research to be possible, more work must be done in establishing the pollutant removal rates and costs of implementing several BMPs on one site. In addition, future research can focus on performing a life cycle assessment for different combinations of BMPs to determine if innovative stormwater management practices have cost saving benefits when evaluating them over their entire lifespan.

5.6. Conclusions

This research has shown that it is feasible to implement innovative stormwater management technologies on Air Force installations. The deterministic analysis and sensitivity analysis performed as part of the VFT process show that three alternatives are generally the most preferred treatment options: grassed swale, infiltration basin, and wet detention. However, sensitivity analysis does suggest that another treatment practice may be the best alternative is there is a very specific contaminant problem that must be addressed. With increased stormwater regulations and rising costs of cleanup and remediation projects, innovative stormwater management technologies can help Air Force bases to comply with regulations and to avoid the high costs associated with polluting local water sources.

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14. ABSTRACT

Stormwater runoff occurs naturally after every storm event; however, traditional development practices have created many impervious surfaces that increase runoff volume and flow rate. Conventional stormwater management practices focus on collecting runoff into centralized channels and conveying it to local bodies of water. This type of conveyance system decreases the opportunity for stormwater to naturally infiltrate. It also prevents contaminants from being naturally filtered out of stormwater flows. As a result, centralized conveyance systems can cause flooding, erosion, and terrestrial/aquatic habitat degradation. Innovative stormwater management strategies treat stormwater on-site by encouraging infiltration, decreasing flow rates, and reducing pollutant loads.

Value-Focused Thinking (VFT) was used in this research to develop a decision analysis model to assist Air Force decision makers in evaluating and selecting innovative stormwater management strategies. VFT is a multi-objective decision analysis model that compares alternatives based on the values of the decision maker. Nine stormwater technologies were evaluated across thirteen evaluation measures. Through deterministic analysis and sensitivity analysis, a grassed swale was found to be the top alternative, followed very closely by the infiltration basin and wet detention options. VFT proved to be a useful methodology in producing an objective solution to this complex, multi-objective decision problem.

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